

## Middlesex University Research Repository:

an open access repository of  
Middlesex University research

<http://eprints.mdx.ac.uk>

Prior, Stephen D, 1993.  
Investigations into the design of a wheelchair-mounted rehabilitation  
robotic manipulator.  
Available from Middlesex University's Research Repository.

---

### Copyright:

Middlesex University Research Repository makes the University's research available electronically.

Copyright and moral rights to this thesis/research project are retained by the author and/or other copyright owners. The work is supplied on the understanding that any use for commercial gain is strictly forbidden. A copy may be downloaded for personal, non-commercial, research or study without prior permission and without charge. Any use of the thesis/research project for private study or research must be properly acknowledged with reference to the work's full bibliographic details.

This thesis/research project may not be reproduced in any format or medium, or extensive quotations taken from it, or its content changed in any way, without first obtaining permission in writing from the copyright holder(s).

If you believe that any material held in the repository infringes copyright law, please contact the Repository Team at Middlesex University via the following email address:  
[eprints@mdx.ac.uk](mailto:eprints@mdx.ac.uk)

The item will be removed from the repository while any claim is being investigated.

# **INVESTIGATIONS INTO THE DESIGN OF A WHEELCHAIR-MOUNTED REHABILITATION ROBOTIC MANIPULATOR**

Stephen D. PRIOR, BEng (Hons), FTC, AMIMechE

A thesis submitted for the degree of Doctor of Philosophy of  
Middlesex University

September 1993

*School of Mechanical & Manufacturing Engineering  
Faculty of Technology  
Middlesex University  
London, U.K.*

## *Abstract*

---

This research describes the steps towards the development of a low-cost wheelchair-mounted manipulator for use by the physically disabled and elderly.

A detailed review of world rehabilitation robotics research has been conducted, covering fifty-six projects. This identified the main areas of research, their scope and results. From this review, a critical investigation of past and present wheelchair-mounted robotic arm projects was undertaken. This led to the formulation of the key design parameters in a final design specification.

The results of a questionnaire survey of fifty electric wheelchair users is presented, which has for the first time established the needs and abilities of this disability group.

An analysis of muscle type actuators, which mimic human muscle, is presented and their application to robotics, orthotics and prosthetics is given. A new type of rotary pneumatic muscle actuator, the flexator, is introduced and through extensive testing its performance characteristics elucidated.

A review of direct-drive rotary pneumatic, hydraulic and electrical actuators has highlighted their relative performance characteristics and has rated their efficiency in terms of their peak torque to motor mass ratio,  $T_p/MM$ . From this, the flexator actuator has been shown to have a higher  $T_p/MM$  ratio than most conventional actuators.

A novel kinematic arrangement is presented which combines the best features of the SCARA and vertically articulated industrial robot geometries, to form the 'Scaricated' arm design. The most appropriate actuator for each joint of this hybrid manipulator was selected, based on the criteria of high  $T_p/MM$  ratio, low cost, safety and compatibility. The final design incorporates conventional pneumatic linear double-acting cylinders, a vane type rotary actuator, two dual flexator actuators, and stepping motors for the fine control of the wrist/end effector.

An ACSL simulation program has been developed which uses mass flow rate equations, based on one-dimensional compressible flow theory and suppressed critical pressure ratios, to simulate the dual flexator actuator. Theoretical and empirical data is compared and shows a high degree of correlation between results.

Finally, the design and development work on two prototypes is discussed. The latest prototype consists of a five-axis manipulator whose pneumatic joints are driven by pulse width modulated solenoid valves. An 8051 microprocessor with proportional error feedback modifies the mark to space ratio of the PWM signal in proportion to the angular error of the joints. This enables control over individual joint speeds, reprogrammable memory locations and position monitoring of each joint.

The integration of rehabilitation robotic manipulators into the daily lives of the physically disabled and elderly will significantly influence the role of personal rehabilitation in the next century.

# Contents

Page

|   |           |
|---|-----------|
| Abstract . . . . .  | ii        |
| Contents . . . . .  | iii       |
| List of Figures . . . . .   | xiii      |
| List of Tables . . . . .  | xvi       |
| Acknowledgements . . . . .  | xvii      |
| <b>1 INTRODUCTION . . . . .</b>   | <b>1</b>  |
| <b>1.1 BACKGROUND . . . . .</b>   | <b>1</b>  |
| <b>1.2 REHABILITATION ROBOTICS . . . . .</b>                            | <b>2</b>  |
| 1.2.1 Industrial Robot Definitions . . . . .                            | 2         |
| 1.2.2 Robotic Workstations . . . . .                                    | 3         |
| 1.2.3 Mobile Robots . . . . .   | 3         |
| 1.2.4 Previous Work . . . . .   | 4         |
| <b>1.3 HUMAN FACTORS, ERGONOMICS AND DISABILITY . . . . .</b>           | <b>5</b>  |
| 1.3.1 Human Factors Information . . . . .                               | 6         |
| 1.3.1.1 <i>The human arm</i> . . . . .                                  | 6         |
| 1.3.2 Ergonomic Data . . . . .  | 9         |
| 1.3.3 Anthropometric Data . . . . .                                     | 10        |
| 1.3.4 Statistical Data . . . . .  | 13        |
| <b>1.4 AIM AND OBJECTIVES OF THE WORK . . . . .</b>                     | <b>15</b> |
| <b>1.5 PREVIEW OF THE THESIS . . . . .</b>                              | <b>16</b> |
| <b>2 WORLD REHABILITATION ROBOTICS RESEARCH . . . . .</b>               | <b>18</b> |
| <b>2.1 INTRODUCTION . . . . .</b>                                       | <b>18</b> |
| <b>2.2 A REVIEW OF WORLD REHABILITATION ROBOTICS RESEARCH . . . . .</b> | <b>19</b> |



|          |  |           |
|----------|--|-----------|
| 2.2.1    | Rehabilitation Robotics Applications . . . . .                       | 19        |
| 2.2.2    | Discussion of the World Review . . . . .                             | 20        |
| 2.3      | A REVIEW OF WHEELCHAIR-MOUNTED ROBOTIC ARM PROJECTS . . . . .        | 22        |
| 2.3.1    | V.A. Rehabilitation Engineering Center, USA . . . . .                | 22        |
| 2.3.2    | Spar Aerospace//Ontario Crippled Children's Centre, Canada . . . . . | 24        |
| 2.3.3    | University of Virginia, USA . . . . .                                | 26        |
| 2.3.4    | Zeelenberg//New Jersey Medical School, USA . . . . .                 | 27        |
| 2.3.5    | The Institute for Rehabilitation Research, The Netherlands . . . . . | 29        |
| 2.3.6    | Bath Institute of Medical Engineering, UK . . . . .                  | 30        |
| 2.3.7    | Inventaid Wheelchair Manipulator, UK . . . . .                       | 32        |
| 2.3.7.1  | <i>Evaluation of the inventaid manipulator</i> . . . . .             | 33        |
| 2.3.7.2  | <i>Aesthetics and ergonomics</i> . . . . .                           | 34        |
| 2.3.7.3  | <i>Human computer interfaces (H.C.I.)</i> . . . . .                  | 34        |
| 2.3.7.4  | <i>Critical analysis of the control pad H.C.I.</i> . . . . .         | 35        |
| 2.3.8    | The Alfred I. duPont Institute, USA . . . . .                        | 36        |
| 2.4      | CONCLUSIONS . . . . .  | 37        |
| <b>3</b> | <b>INVESTIGATION OF USER REQUIREMENTS . . . . .</b>                  | <b>39</b> |
| 3.1      | INTRODUCTION . . . . .   | 39        |
| 3.2      | THE BATH SURVEY CONCLUSIONS . . . . .                                | 40        |
| 3.3      | THE MIDDLESEX ROBOTIC AID QUESTIONNAIRE . . . . .                    | 40        |
| 3.3.1    | Method of Survey . . . . .   | 41        |
| 3.3.2    | Subject Criteria . . . . .   | 41        |
| 3.3.3    | Results . . . . .  | 41        |
| 3.3.3.1  | <i>Age distribution</i> . . . . .                                    | 42        |
| 3.3.3.2  | <i>Sex distribution</i> . . . . .                                    | 42        |
| 3.3.3.3  | <i>Marital status</i> . . . . .                                      | 42        |
| 3.3.3.4  | <i>Type of abode</i> . . . . .                                       | 42        |

|          |  |    |
|----------|--|----|
| 3.3.3.5  | <i>Analysis of subjects living at home</i>                         | 45 |
| 3.3.3.6  | <i>Employment of survey subjects</i>                               | 45 |
| 3.3.3.7  | <i>Pastimes</i>  | 45 |
| 3.3.3.8  | <i>Spinal cord injuries</i>  | 45 |
| 3.3.3.9  | <i>Percentage of subjects suffering from involuntary movements</i> | 49 |
| 3.3.3.10 | <i>Type of disability</i>  | 49 |
| 3.3.3.11 | <i>Personal hygiene tasks</i>                                      | 49 |
| 3.3.3.12 | <i>Domestic tasks</i>  | 49 |
| 3.3.3.13 | <i>Leisure &amp; recreational tasks</i>                            | 51 |
| 3.3.3.14 | <i>Working environment tasks</i>                                   | 51 |
| 3.3.3.15 | <i>Top five tasks</i>  | 51 |
| 3.3.3.16 | <i>Possible consumer population</i>                                | 51 |
| 3.3.3.17 | <i>Input device familiarity</i>                                    | 51 |
| 3.3.3.18 | <i>Practical trial stage</i>                                       | 53 |
| 3.4      | THE QUEEN MARGARET COLLEGE SURVEY                                  | 53 |
| 3.4.1    | Summary of the Survey Results                                      | 53 |
| 3.4.2    | Most Important Task Lists  | 54 |
| 3.5      | QUESTIONNAIRE RESULTS AND THE DESIGN SPECIFICATION                 | 54 |
| 3.5.1    | Summary of the Questionnaire Results                               | 55 |
| 3.5.2    | Most Important Task Lists (Middlesex Questionnaire Results)        | 55 |
| 3.5.3    | The Weighted Matrix Method   | 56 |
| 3.5.3.1  | <i>Weighted matrix results</i>                                     | 56 |
| 3.6      | CLINICAL EVALUATION OF THE MASTER SYSTEM                           | 58 |
| 3.6.1    | Population Characteristics   | 59 |
| 3.6.2    | Feedback from the Survey Subjects                                  | 59 |
| 3.7      | CONCLUSIONS  | 59 |

- 4 THE DESIGN SPECIFICATION . . . . . 61**
- 4.1 INTRODUCTION . . . . . 61
- 4.2 PRELIMINARY DESIGN SPECIFICATION . . . . . 61
  - 4.2.1 Scope . . . . . 61
  - 4.2.2 Related Documents . . . . . 61
  - 4.2.3 Terminology . . . . . 62
  - 4.2.4 General Requirements . . . . . 62
  - 4.2.5 Design Requirements . . . . . 62
  - 4.2.6 Environmental Conditions . . . . . 63
  - 4.2.7 Ergonomics and Aesthetics . . . . . 63
  - 4.2.8 Safety . . . . . 63
  - 4.2.9 Cost and Servicing . . . . . 63
- 4.3 FINAL DESIGN SPECIFICATION . . . . . 64
  - 4.3.1 Scope . . . . . 64
  - 4.3.2 Related Documents . . . . . 64
  - 4.3.3 Terminology . . . . . 64
  - 4.3.4 General Requirements . . . . . 65
  - 4.3.5 Design Requirements . . . . . 65
  - 4.3.6 Environmental Conditions . . . . . 66
  - 4.3.7 Ergonomics and Aesthetics . . . . . 66
  - 4.3.8 Safety . . . . . 66
  - 4.3.9 Cost . . . . . 67
  - 4.3.10 Life Expectancy and Servicing . . . . . 67
- 4.4 CONCLUSIONS . . . . . 67
- 5 HUMAN MUSCLE AND ITS ARTIFICIAL EQUIVALENT . . . . . 69**
- 5.1 INTRODUCTION . . . . . 69
  - 5.1.1 Pneumatic Muscle Type Actuators . . . . . 71

|         |   |     |
|---------|---|-----|
| 5.1.2   | Controllable Compliance . . . . .   | 74  |
| 5.1.3   | External Power Source Criteria . . . . .  | 75  |
| 5.1.4   | The Flexator™ Pneumatic Muscle Actuator . . . . .   | 75  |
| 5.1.4.1 | <i>Design advantages of using flexators</i> . . . . .   | 76  |
| 5.1.4.2 | <i>Experimental testing</i> . . . . .   | 77  |
| 5.1.4.3 | <i>Flexator hysteresis and non-linearity</i> . . . . .  | 77  |
| 5.2     | COMPARATIVE PERFORMANCE OF THE FLEXATOR WITH OTHER<br>FORMS OF DIRECT-DRIVE ROTARY ACTUATOR . . . . . | 79  |
| 5.2.1   | Conventional Pneumatic and Hydraulic Rotary Actuators . . . . .                                       | 79  |
| 5.2.1.1 | <i>Vane type rotary actuators</i> . . . . .   | 80  |
| 5.2.1.2 | <i>Rack &amp; pinion type rotary actuators</i> . . . . .  | 81  |
| 5.2.1.3 | <i>Planetary helical type rotary actuators</i> . . . . .  | 82  |
| 5.2.2   | Conventional Electrical Rotary Actuators . . . . .  | 83  |
| 5.2.2.1 | <i>Permanent magnet dc servo motors</i> . . . . .   | 84  |
| 5.2.2.2 | <i>Stepper motors</i> . . . . .   | 85  |
| 5.2.2.3 | <i>Rotary solenoids</i> . . . . .   | 86  |
| 5.2.3   | Summary . . . . .   | 86  |
| 5.3     | THEORETICAL ANALYSIS . . . . .  | 87  |
| 5.3.1   | Limiting Conditions & Experimental Results . . . . .  | 91  |
| 5.4     | SINGLE FLEXATOR PERFORMANCE TESTING & ANALYSIS . . . . .  | 92  |
| 5.4.1   | Single Flexator Test Results . . . . .  | 93  |
| 5.4.1.1 | <i>Hysteresis analysis</i> . . . . .  | 94  |
| 5.4.1.2 | <i>Flexator air temperature analysis</i> . . . . .  | 98  |
| 5.4.1.3 | <i>Time delay and supply line pressure drop</i> . . . . .   | 99  |
| 5.5     | INVESTIGATIONS INTO ANTAGONISTIC FLEXATOR PAIRS . . . . .   | 101 |
| 5.5.1   | Description of the Dual Flexator Actuator . . . . .   | 101 |
| 5.5.2   | Testing the Theory of Controllable Compliance . . . . .   | 101 |
| 5.5.3   | Testing the Dynamic Performance of the Dual Flexator Actuator . . . . .                               | 103 |

|         |   |     |
|---------|---|-----|
| 5.5.3.1 | <i>The dual flexator pressure-volume diagram</i>                        | 104 |
| 5.5.3.2 | <i>Measurement of the dynamic control variables</i>                     | 105 |
| 5.6     | SIMULATION OF THE DUAL FLEXATOR ROTARY ACTUATOR USING ACSL              | 107 |
| 5.6.1   | Description of the Physical System                                      | 107 |
| 5.6.2   | Equations of Motion of the Actuator                                     | 108 |
| 5.6.3   | Controller Design   | 108 |
| 5.6.4   | Experimental Data on the 60 x 90 Dual Flexator Actuator                 | 110 |
| 5.6.5   | Proportional Flow Calculation   | 111 |
| 5.6.6   | Determination of the Static and Dynamic Friction Constants              | 111 |
| 5.6.7   | Flexator Theoretical Torque Analysis                                    | 113 |
| 5.6.7.1 | <i>Torque analysis of the flexator actuator</i>                         | 114 |
| 5.6.8   | Simulation Results  | 118 |
| 5.6.8.1 | <i>Determination of the flexator/webbing strap frictional constants</i> | 118 |
| 5.7     | CONCLUSIONS   | 120 |
| 6       | KINEMATIC DESIGN OF THE MIDDLESEX MANIPULATOR                           | 122 |
| 6.1     | INTRODUCTION  | 122 |
| 6.1.1   | Needs of the User   | 122 |
| 6.1.2   | The SCARA Geometry  | 124 |
| 6.1.3   | The Wheelchair-Mounted Application                                      | 125 |
| 6.1.4   | The Scariculated Arm Design   | 127 |
| 6.1.4.1 | <i>Design philosophy and control</i>                                    | 127 |
| 6.2     | PARAMETRIC DESIGN OF THE SCARICULATED ARM GEOMETRY                      | 128 |
| 6.2.1   | Parametric Equation Definitions   | 129 |
| 6.2.1.1 | <i>Initial values for the design variables</i>                          | 130 |
| 6.2.2   | The Scariculated Workspace  | 131 |
| 6.3     | CONCLUSIONS   | 132 |

|          |  |            |
|----------|--|------------|
| <b>7</b> | <b>DESIGN &amp; DEVELOPMENT OF A MULTI-AXIS PROTOTYPE ARM . . .</b>      | <b>133</b> |
| 7.1      | INTRODUCTION . . . . .   | 133        |
| 7.2      | FULL-SIZED SIGHT MODEL . . . . .   | 133        |
| 7.3      | SELECTION OF THE PROTOTYPE'S JOINT ACTUATORS . . . . .                   | 135        |
| 7.3.1    | Joint 1 - Vertical Lift Actuator . . . . .                               | 135        |
| 7.3.2    | Joint 2 - Shoulder Joint Actuator . . . . .                              | 136        |
| 7.3.3    | Joint 3 - Mode Change Joint Actuator . . . . .                           | 136        |
| 7.3.4    | Joint 4 - Elbow Joint Actuator . . . . .                                 | 137        |
| 7.3.5    | Joint 5 - Wrist Extension Actuator . . . . .                             | 137        |
| 7.3.6    | Joints 6, 7 and 8 - Wrist Yaw & Roll and End Effector Grasp . . . . .    | 137        |
| 7.4      | DESIGN OF THE FIRST PROTOTYPE ARM . . . . .                              | 138        |
| 7.4.1    | Detailed Mechanical Design . . . . .                                     | 138        |
| 7.4.2    | Selection of the Link Enclosure Type . . . . .                           | 139        |
| 7.4.2.1  | <i>Factors affecting the optimum design variables</i> . . . . .          | 140        |
| 7.4.3    | Manufacture and Assembly of the First Prototype Arm . . . . .            | 141        |
| 7.4.4    | Cable and Hose Routing on the First Prototype Arm . . . . .              | 143        |
| 7.4.5    | Selection of the Fluid Control Valves for the Pneumatic Joints . . . . . | 144        |
| 7.4.5.1  | <i>Method of joint control using VJ114 valves</i> . . . . .              | 145        |
| 7.4.5.2  | <i>Pulse width modulation (p.w.m) of VJ114 valves</i> . . . . .          | 146        |
| 7.4.6    | Control System Design . . . . .  | 146        |
| 7.4.6.1  | <i>System architecture</i> . . . . .                                     | 147        |
| 7.4.7    | Controller Hardware Description . . . . .                                | 148        |
| 7.4.7.1  | <i>Microcontroller INTEL 8051</i> . . . . .                              | 148        |
| 7.4.7.2  | <i>Quartz crystal 8Mhz/12Mhz</i> . . . . .                               | 149        |
| 7.4.7.3  | <i>Power driver CA3242</i> . . . . .                                     | 149        |
| 7.4.7.4  | <i>A/D converter TLC549IP</i> . . . . .                                  | 149        |
| 7.4.7.5  | <i>Voltage regulator L78S05</i> . . . . .                                | 150        |

|          |  |     |
|----------|--|-----|
| 7.4.7.6  | <i>Dataselector 74LS151</i>                                      | 150 |
| 7.4.7.7  | <i>Demultiplexer/Decoder 74LS138</i>                             | 150 |
| 7.4.7.8  | <i>Demultiplexer/Decoder 74LS154</i>                             | 150 |
| 7.4.7.9  | <i>Inverter 74LSS04</i>  | 150 |
| 7.4.7.10 | <i>Potentiometer 10K</i>   | 150 |
| 7.4.7.11 | <i>User interface</i>  | 151 |
| 7.4.8    | Production of the Printed Circuit Board                          | 151 |
| 7.4.9    | Controller Software Development                                  | 151 |
| 7.4.9.1  | <i>Software requirements</i>                                     | 152 |
| 7.4.10   | Main Realised Functions  | 153 |
| 7.4.10.1 | <i>Emergency stop</i>  | 153 |
| 7.4.10.2 | <i>User input</i>  | 153 |
| 7.4.10.3 | <i>Position control</i>  | 154 |
| 7.4.11   | Human Robot Interface (H.R.I)                                    | 154 |
| 7.4.11.1 | <i>Functional description of the keypad interface</i>            | 155 |
| 7.5      | MANIFOLD DESIGN AND CONSTRUCTION                                 | 156 |
| 7.6      | FLOW RATE ANALYSIS OF THE VJ114 SOLENOID VALVE                   | 157 |
| 7.6.1    | Experimental Measurement of Flow Rate                            | 159 |
| 7.6.2    | Mathematical Modelling of Mass Flow Rates                        | 160 |
| 7.6.3    | Empirical Analysis of Critical Pressure Ratios, $b_1$ and $b_2$  | 163 |
| 7.6.4    | Results of the Mass Flow Rate Analysis                           | 165 |
| 7.7      | TESTING OF THE FIRST PROTOTYPE ARM                               | 166 |
| 7.8      | INVESTIGATIONS INTO THE PERFORMANCE OF THE VJ114 VALVE USING PWM | 167 |
| 7.8.1    | Effect on the Flow Rate of Varying the PWM Frequency             | 168 |
| 7.8.2    | Effect on the Flow Rate of Varying the Mark to Space Ratio       | 169 |
| 7.8.3    | Natural Frequency Analysis of the VJ114 Valve                    | 170 |
| 7.8.4    | Testing of a Dual Flexator Actuator with PWM                     | 170 |

|          |  |                  |
|----------|--|------------------|
| 7.9      | REDESIGN OF THE FIRST PROTOTYPE ARM . . . . .  | 171              |
| 7.9.1    | Selection of the Second Prototype's Joint Actuators . . . . .  | 171              |
| 7.9.1.1  | <i>Joint 1 - vertical lift actuator</i> . . . . .  | 171              |
| 7.9.1.2  | <i>Joint 2 - shoulder joint actuator</i> . . . . .   | 172              |
| 7.9.1.3  | <i>Joint 3 - mode change joint actuator</i> . . . . .  | 173              |
| 7.9.1.4  | <i>Joint 4 - elbow joint actuator</i> . . . . .  | 173              |
| 7.9.1.5  | <i>joint 5 - wrist extension actuator</i> . . . . .  | 173              |
| 7.9.1.6  | <i>Joints 6, 7 and 8 - wrist yaw &amp; roll and end effector grasp</i> . . . . .   | 174              |
| 7.10     | DESIGN OF THE SECOND PROTOTYPE ARM . . . . .   | 174              |
| 7.10.1   | Detailed Mechanical Design . . . . .   | 174              |
| 7.10.1.1 | <i>Selection of the link enclosure type</i> . . . . .  | 175              |
| 7.10.2   | Factors Affecting the Optimum Design Variables . . . . .   | 175              |
| 7.10.3   | Discussion of the New PWM Control Algorithm . . . . .  | 176              |
| 7.11     | CONCLUSIONS . . . . .  | 178              |
| <b>8</b> | <b>CONCLUSIONS &amp; FURTHER WORK . . . . .</b>  | <b>179</b>       |
| 8.1      | CONCLUSIONS . . . . .  | 179              |
| 8.2      | FURTHER WORK . . . . .   | 185              |
| 8.2.1    | Introduction . . . . .   | 185              |
| 8.2.2    | Improvements to the Dual Flexator Actuator . . . . .   | 185              |
| 8.2.3    | Development of the ACSL Simulation Model . . . . .   | 186              |
| 8.2.4    | Design of the Wrist and End Effector for the Middlesex Manipulator . . . . .   | 186              |
| 8.2.5    | Investigations into the Role of Preprogrammed and Direct Teleoperation with<br>Reference to the Priority Task List . . . . . | 186              |
|          | List of References . . . . .   | 187              |
|          | <i>Appendix A - Middlesex Questionnaire Survey . . . . .</i>   | <i>A.1-A.5</i>   |
|          | <i>Appendix B1 - Comparison of Pneumatic &amp; Hydraulic Rotary Direct-Drive Actuators . . . . .</i>                         | <i>B1.1-B1.6</i> |
|          | <i>Appendix B2 - Comparison of Pneumatic &amp; Electric Rotary Direct-Drive Actuators . . . . .</i>                          | <i>B2.1-B2.2</i> |
|          | <i>Appendix C - Flexator Volumetric Measurements . . . . .</i>   | <i>C.1-C.2</i>   |



|                    |  |           |                   |
|--------------------|--|-----------|-------------------|
| <i>Appendix D</i>  | - <i>Flexator Test-Rig Working Drawings</i>            | . . . . . | <i>D.1-D.4</i>    |
| <i>Appendix E</i>  | - <i>Flexator Actuator Frictional Losses</i>           | . . . . . | <i>E.1-E.5</i>    |
| <i>Appendix F1</i> | - <i>Flexator Actuator Static Test Results</i>         | . . . . . | <i>F1.1-F1.12</i> |
| <i>Appendix F2</i> | - <i>Table of Flexator Hysteresis Values</i>           | . . . . . | <i>F2.1</i>       |
| <i>Appendix G</i>  | - <i>Flexator Air Temperature Analysis</i>             | . . . . . | <i>G.1-G.4</i>    |
| <i>Appendix H</i>  | - <i>Time Delay &amp; Supply Line Pressure Drop</i>    | . . . . . | <i>H.1-H.2</i>    |
| <i>Appendix J</i>  | - <i>Stiffness Data for Dual Flexator Actuator</i>     | . . . . . | <i>J.1-J.9</i>    |
| <i>Appendix K</i>  | - <i>ACSL Simulation of Dual Flexator Actuator</i>     | . . . . . | <i>K.1-K.8</i>    |
| <i>Appendix L</i>  | - <i>Working Drawings of the First Prototype</i>       | . . . . . | <i>L.1-L.6</i>    |
| <i>Appendix M</i>  | - <i>Dual Flexator Actuator Design Tables</i>          | . . . . . | <i>M.1-M.2</i>    |
| <i>Appendix N</i>  | - <i>Controller Hardware Description</i>               | . . . . . | <i>N.1-N.9</i>    |
| <i>Appendix P</i>  | - <i>Assembler Computer Program to Control the Arm</i> | . . . . . | <i>P.1-P.21</i>   |
| <i>Appendix Q</i>  | - <i>Working Drawing of the Main Manifold Block</i>    | . . . . . | <i>Q.1</i>        |
| <i>Appendix R</i>  | - <i>Effect of PWM Frequency on Actuator Stroke</i>    | . . . . . | <i>R.1-R.8</i>    |
| <i>Appendix S</i>  | - <i>Second Prototype Designs</i>                      | . . . . . | <i>S.1 - S.3</i>  |

**Published Work**

# List of Figures

|   | <i>Page</i> |
|---|-------------|
| <b>Chapter 1</b>  |             |
| <i>Fig. 1.1 - The human arm .....</i>   | <i>7</i>    |
| <i>Fig. 1.2 - Reach characteristics of paraplegics .....</i>                                | <i>11</i>   |
| <i>Fig. 1.3 - Dimensions of adult wheelchair users.....</i>                                 | <i>12</i>   |
| <i>Fig. 1.4 - Blind regions around the base of a vessa vitesse powered wheelchair .....</i> | <i>13</i>   |
| <b>Chapter 2</b>  |             |
| <i>Fig. 2.1 - World rehabilitation robotics survey .....</i>                                | <i>20</i>   |
| <i>Fig. 2.2 - VA Rehabilitation engineering center c.1974 .....</i>                         | <i>23</i>   |
| <i>Fig. 2.3 - NASA Jet propulsion laboratory arm c.1975 .....</i>                           | <i>24</i>   |
| <i>Fig. 2.4 - Spar aerospace/O.C.C.C. arm c.1977.....</i>                                   | <i>25</i>   |
| <i>Fig. 2.5 - University of virginia arm c.1978 .....</i>                                   | <i>27</i>   |
| <i>Fig. 2.6 - The manus manipulator c.1988.....</i>   | <i>30</i>   |
| <i>Fig. 2.7 - Bath institute of medical engineering's conceptual arm c.1991 .....</i>       | <i>32</i>   |
| <i>Fig. 2.8 - Inventaid wheelchair-mounted manipulator c.1992 .....</i>                     | <i>33</i>   |
| <b>Chapter 3</b>  |             |
| <i>Fig. 3.1 - Age distribution of survey subjects.....</i>                                  | <i>43</i>   |
| <i>Fig. 3.2 - Marital status of survey subjects .....</i>                                   | <i>43</i>   |
| <i>Fig. 3.3 - Marital status and type of work.....</i>                                      | <i>44</i>   |
| <i>Fig. 3.4 - Type of abode of survey subjects.....</i>                                     | <i>44</i>   |
| <i>Fig. 3.5 - Analysis of subjects living at home.....</i>                                  | <i>46</i>   |
| <i>Fig. 3.6 - Care assistance of subjects living at home.....</i>                           | <i>46</i>   |
| <i>Fig. 3.7 - Employment status of survey subjects .....</i>                                | <i>47</i>   |
| <i>Fig. 3.8 - Most popular pastimes .....</i>   | <i>47</i>   |
| <i>Fig. 3.9 - Spinal cord injuries : lesion level frequency .....</i>                       | <i>48</i>   |
| <i>Fig. 3.10 - Spinal cord injuries : level of disability .....</i>                         | <i>48</i>   |
| <i>Fig. 3.11 - Involuntary movement of survey subjects.....</i>                             | <i>50</i>   |
| <i>Fig. 3.12 - Type of disability .....</i>   | <i>50</i>   |
| <i>Fig. 3.13 - Possible task list of a robotic aid .....</i>                                | <i>52</i>   |
| <i>Fig. 3.14 - Subjects likely to purchase a robotic aid.....</i>                           | <i>52</i>   |
| <b>Chapter 5</b>  |             |
| <i>Fig. 5.1 - Human muscle control circuit and feedback path.....</i>                       | <i>69</i>   |
| <i>Fig. 5.2 - Relationship between efficiency and force ratio .....</i>                     | <i>70</i>   |
| <i>Fig. 5.3 - Endurance performance of human muscle .....</i>                               | <i>71</i>   |
| <i>Fig. 5.4 - The McKibben artificial muscle .....</i>                                      | <i>72</i>   |
| <i>Fig. 5.5 - Rubbertuator driven Bridgestone/Hitachi robot .....</i>                       | <i>73</i>   |

|  |            |
|--|------------|
| <i>Fig. 5.6 - ROMAC actuator with arcuate lobes .....</i>                                      | <i>73</i>  |
| <i>Fig. 5.7 - Controllable compliance of antagonistic muscles.....</i>                         | <i>74</i>  |
| <i>Fig. 5.8 - Flexator rotary actuator experimental test-rig .....</i>                         | <i>76</i>  |
| <i>Fig. 5.9 - Static test showing non-linearity &amp; hysteresis .....</i>                     | <i>78</i>  |
| <i>Fig. 5.10- Vane type rotary actuator .....</i>  | <i>80</i>  |
| <i>Fig. 5.11- Rack &amp; pinion type rotary actuator .....</i>                                 | <i>81</i>  |
| <i>Fig. 5.12- Planetary helical rotary actuator .....</i>                                      | <i>82</i>  |
| <i>Fig. 5.13- DC motor excitation .....</i>  | <i>83</i>  |
| <i>Fig. 5.14- Hybrid stepping motor .....</i>  | <i>86</i>  |
| <i>Fig. 5.15- Thermodynamic schematic of a single flexator .....</i>                           | <i>88</i>  |
| <i>Fig. 5.16- Variation of efficiency with load torque .....</i>                               | <i>91</i>  |
| <i>Fig. 5.17- Schematic of test-rig data acquisition system .....</i>                          | <i>93</i>  |
| <i>Fig. 5.18- Measurement of flexator internal air pressure.....</i>                           | <i>95</i>  |
| <i>Fig. 5.19- Flexator volumetric test showing hysteresis.....</i>                             | <i>96</i>  |
| <i>Fig. 5.20- Typical actuator with and without friction.....</i>                              | <i>98</i>  |
| <i>Fig. 5.21- Schematic of dual flexator rotary actuator .....</i>                             | <i>101</i> |
| <i>Fig. 5.22- Controllable compliance of the dual flexator.....</i>                            | <i>102</i> |
| <i>Fig. 5.23- Linear stiffness with constant pressure ratio.....</i>                           | <i>103</i> |
| <i>Fig. 5.24- Dual flexator cycling stiffness .....</i>  | <i>104</i> |
| <i>Fig. 5.25- PV diagram for the dual flexator actuator.....</i>                               | <i>105</i> |
| <i>Fig. 5.26- Dynamic measurement of variables at torque load of 0.1 Nm.....</i>               | <i>106</i> |
| <i>Fig. 5.27- Dynamic measurement of variables at torque load of 11.2 Nm.....</i>              | <i>106</i> |
| <i>Fig. 5.28- The dual flexator actuator represented as a vane type actuator .....</i>         | <i>107</i> |
| <i>Fig. 5.29- Graph of flexator volume against angular displacement .....</i>                  | <i>110</i> |
| <i>Fig. 5.30- Measurement of the test-rig viscous friction coefficient.....</i>                | <i>112</i> |
| <i>Fig. 5.31- Model of a single flexator rotary actuator .....</i>                             | <i>114</i> |
| <i>Fig. 5.32- Variation of theoretical torque with wrap around angle and flat width .....</i>  | <i>116</i> |
| <i>Fig. 5.33- Sine wave theoretical torque output of the 60 series flexator actuator .....</i> | <i>117</i> |
| <i>Fig. 5.34- Simulated and experimental chamber pressures (60 x 90 flexator).....</i>         | <i>119</i> |
| <i>Fig. 5.35- Simulated and experimental angular displacement data (60 x 90 flexator).....</i> | <i>119</i> |

## **Chapter 6**

|  |            |
|--|------------|
| <i>Fig. 6.1 - Surveys of industrial robot geometries.....</i>          | <i>123</i> |
| <i>Fig. 6.2 - RTX robot showing SCARA configuration .....</i>          | <i>124</i> |
| <i>Fig. 6.3 - SCARA concept with telescopic z-axis .....</i>           | <i>126</i> |
| <i>Fig. 6.4 - Scariculated arm geometry, designed using CATIA.....</i> | <i>127</i> |
| <i>Fig. 6.5 - Parametric design of the scariculated arm .....</i>      | <i>128</i> |
| <i>Fig. 6.6 - Plan view of Scariculated workspace geometry.....</i>    | <i>131</i> |

## **Chapter 7**

|  |            |
|--|------------|
| <i>Fig. 7.1 - Full-sized sight model .....</i> | <i>134</i> |
|--|------------|

|  |     |
|--|-----|
| <i>Fig. 7.2 - Prototype arm's joint arrangement</i> .....                                  | 134 |
| <i>Fig. 7.3 - Detailed design of the first prototype arm</i> .....                         | 141 |
| <i>Fig. 7.4 - VJ114 valve internal tappings</i> .....                                      | 145 |
| <i>Fig. 7.5 - Schematic of valve layout</i> .....  | 145 |
| <i>Fig. 7.6 - Effect of mark to space ratio on valve flowrate</i> .....                    | 146 |
| <i>Fig. 7.7 - Microprocessor controlled system configuration</i> .....                     | 148 |
| <i>Fig. 7.8 - Main control flow chart</i> .....  | 152 |
| <i>Fig. 7.9 - Keypad layout and I/O channels</i> .....                                     | 155 |
| <i>Fig. 7.10- Sectional view of manifold block &amp; valves</i> .....                      | 156 |
| <i>Fig. 7.11- Shaded image of manifold, designed using IDEAS</i> .....                     | 157 |
| <i>Fig. 7.12- Experimental measurement of valve flow rates</i> .....                       | 159 |
| <i>Fig. 7.13- Flow rate test of VJ114 solenoid valve</i> .....                             | 160 |
| <i>Fig. 7.14- Flow rate test of VJ114A solenoid valve</i> .....                            | 160 |
| <i>Fig. 7.15- Mass flow rate analysis : chamber 1 charging</i> .....                       | 164 |
| <i>Fig. 7.16- Mass flow rate analysis : chamber 2 venting</i> .....                        | 164 |
| <i>Fig. 7.17- Oscillatory nature of joint 2</i> .....                                      | 167 |
| <i>Fig. 7.18- Effect on the VJ114 valve's flow rate of varying the PWM frequency</i> ..... | 168 |
| <i>Fig. 7.19- Variation of the % max flow rate with the % mark time</i> .....              | 169 |
| <i>Fig. 7.20- Effect of PWM frequency on joint stroke times</i> .....                      | 171 |

# *List of Tables*

|   | <i>Page</i> |
|---|-------------|
| <b>Chapter 1</b>  |             |
| <i>Table 1.1 - Human Arm Performance.....</i>   | <i>8</i>    |
| <i>Table 1.2 - Human Arm Resonant Frequencies and Lengths .....</i>   | <i>8</i>    |
| <i>Table 1.3 - Centre of Gravity Positions in the Human Arm .....</i>   | <i>9</i>    |
| <i>Table 1.4 - Statistics on Disability in Great Britain .....</i>  | <i>13</i>   |
| <br><b>Chapter 3</b>  |             |
| <i>Table 3.1 - Weighted Matrix Results.....</i>   | <i>57</i>   |
| <i>Table 3.2 - Highest Scoring Tasks (weighted matrix results) .....</i>  | <i>58</i>   |
| <br><b>Chapter 5</b>  |             |
| <i>Table 5.1 - Summary of the Static Test Results .....</i>   | <i>77</i>   |
| <i>Table 5.2 - Comparison of Electrical, Hydraulic and Pneumatic Actuation.....</i>   | <i>79</i>   |
| <i>Table 5.3 - Static Frictional Torque of Test-Rig Bearings .....</i>  | <i>96</i>   |
| <br><b>Chapter 6</b>  |             |
| <i>Table 6.1 - Parametric Design Variables and the Optimum Solution .....</i>   | <i>131</i>  |
| <i>Table 6.2 - Joint Strokes for the Scariculated Arm Geometry .....</i>  | <i>132</i>  |
| <br><b>Chapter 7</b>  |             |
| <i>Table 7.1 - Comparison of Commercially Available Linear Actuators .....</i>  | <i>135</i>  |
| <i>Table 7.2 - Parametric Design Variables and the First Prototype.....</i>   | <i>141</i>  |
| <i>Table 7.3 - Main Component List for the First Prototype .....</i>  | <i>142</i>  |
| <i>Table 7.4 - Overall Mass of Purpose-Built Wheelchair-Mounted Systems.....</i>  | <i>143</i>  |
| <i>Table 7.5 - Logic Table for Joint Control.....</i>   | <i>145</i>  |
| <i>Table 7.6 - Truth Table of the Keypad Output.....</i>  | <i>155</i>  |
| <i>Table 7.7 - Conversion between Flow Coefficients .....</i>   | <i>158</i>  |
| <i>Table 7.8 - Flow Coefficients for the VJ114 Series Solenoid Valves.....</i>  | <i>158</i>  |
| <i>Table 7.9 - Effect on the Modelling Accuracy of the Critical Pressure Ratio .....</i>  | <i>165</i>  |
| <i>Table 7.10 - Piston Rod Deflection and Stress Analysis of Joint 1 .....</i>  | <i>172</i>  |
| <i>Table 7.11 - Parametric Design Variables and the Second Prototype .....</i>  | <i>176</i>  |
| <br><b>Chapter 8</b>  |             |
| <i>Table 8.1 - Component Costs of the Second Prototype.....</i>   | <i>180</i>  |
| <i>Table 8.2 - Summary of Wheelchair-mounted Manipulator Designs .....</i>  | <i>182</i>  |
| <i>Table 8.3 - Comparison Between Conventional Pneumatic and Hydraulic<br/>Direct-Drive Rotary Actuators and the Dual Flexator.....</i> | <i>183</i>  |

## *Acknowledgements*

---

My director of studies, Peter Warner, for steering the course and providing the tea and biscuits. My second supervisors, Dr Keith Wright (Biomet Ltd) and Dr Robin Platts (Royal National Orthopaedic Hospital) and advisors, Anthony White, Tom Parsons (Middlesex University) and Ian Bayley (London Spinal Injuries Unit), for all their help.

My EC placement students, René Bergsma, Jack Thiboudier, Jitze Mink and Peter Öettinger, who worked on the prototype arm manufacture, controller design and system assembly.

To all the many companies who donated materials for the manufacture of the test-rigs and prototype arm designs. To all the individuals and groups who helped with the questionnaire survey.

My funding sources, the Association for Spinal Injury Research, Rehabilitation and Reintegration (ASPIRE), and the National Advisory Body (NAB). Also to The Royal Society, The British Council (Tokyo) and The Royal Academy of Engineering for providing grants to enable me to present my work at international conferences in the US and Japan.

Jim Hennequin for permitting the testing, analysis and use of the flexator actuator at Middlesex.

The technician staff at the Bounds Green campus, especially Peter Burn, Mick Carroll, Jeff Cooper, Charles Ablett, Ron Brick, Nader Salam, Issam Siman and Imtiazali Bhaiji.

My distinguished colleagues with whom I have shared an office, and many constructive discussions with, over the last five years, Dr Mehmet Karamanoglu, Dr Mark Stoker, Yui Wong and Jeremy Lewis.

Staff of the Computer centre, Management Services, PC Support, Media Services especially Clive Clunis, Allan Forde and Ian Slavin, Catering Services and the Library. To those unsung heroes, the campus security staff for putting up with me being the last to leave the site on numerous occasions. To the many friends, past and present, that I have made through Middlesex.

A special thankyou to Eileen in the print room and to Linda Wai Ying Chan for the many hours spent on the Macintosh robotic simulation.

Finally, to my family for supporting me and Don Knight for inspiring me to have a go in the first place.

# Chapter 1

## INTRODUCTION

---

*'To the machine, the work of the machine; to man, the thrill of further creation.'*  
*Kazuma Tateisi, c 1980.*

---

### 1.1 BACKGROUND

The introduction of the first industrial robot (the Unimate) by George C. Devol Jnr and Joseph Engelberger in 1962 was the beginning of a revolution in manufacturing technology which today has seen world installations of robots approaching the 500,000 mark. However, this success was not accomplished without initial problems. The first Unimate robot, based on Devol's patented 'Programmed Article Transfer' device weighed almost 1600 kg and resembled a tank with an end effector mounted on the end of a gun-like turret. It was hydraulically powered with digital feedback and could lift 34 kg, with 150 memory locations. This robot although a 'dinosaur' in comparison to today's state of the art systems was an advanced technical revolution in its day. Even though this device created much interest amongst manufacturers and the media, there were few buyers. Take-up was slow and as a result the Unimation company did not make a profit until 1975, some 21 years after the initial patent was filed, this is a problem shared by most emerging technologies.

Applications of industrial robotics have always focussed on the automotive industry and consequently much of the early research work was directed into this area. Recently however, there has been a steady growth in research in the areas of medical and rehabilitation robotics. The impetus for this growth stems from an increasingly aging world population (Japan: Males 75.4 yrs, Females 81.1)<sup>‡</sup> together with more accurate estimates of the number of disabled individuals (12% of most industrialised nations), their social circumstances and needs. These reasons together with the availability of specific funding (20 Million ECU for the EC Technology Initiative for Disabled and Elderly program) has meant that more emphasis has been placed in the last decade on developing rehabilitation robots and manipulators for use by the elderly or physically disabled. Due to the relatively small market and high price sensitivity, rehabilitation robots are unlikely to become mass produced products. However, they do have the ability to significantly improve the lives of both the frail and the physically disabled.

(‡) U.N. estimates of life expectancy at birth (1985-90).

## 1.2 REHABILITATION ROBOTICS

Rehabilitation robotics is a hybrid term combining the disciplines of industrial robotics and medical rehabilitation.

### 1.2.1 Industrial Robot Definitions:

*Industrial robot:* 'A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialised devices through variable programmed motions for the performance of a variety of tasks.'

(Robot Institute of America, 1979)

*Manipulating industrial robot:* 'An automatically controlled, reprogrammable, multi-purpose, manipulative machine with several degrees of freedom, which may be either fixed in place or mobile for use in industrial automation applications.'

(ISO/TR 8373 : 1988 'Manipulating Industrial Robots - Vocabulary')

*Manipulator:* 'A machine, the mechanism of which usually consists of a series of segments, jointed or sliding relative to one another, for the purpose of grasping and/or moving objects (pieces or tools) usually in several degrees of freedom. It may be controlled by an operator, a programmable electronic controller, or any logic system.'

(ISO/TR 8373 : 1988 'Manipulating Industrial Robots - Vocabulary')

The definitions given above have taken the International Standards Organisation committees many years to agree upon, in fact ever since the first industrial robot was manufactured in 1962, people have been trying to define what an industrial robot actually is. In view of this, there is currently no universally accepted definition of a rehabilitation robot. However, the definition which comes closest to a rehabilitation robot would be the one for the manipulator. Perhaps a more appropriate term for a rehabilitation robot would be a rehabilitation manipulator. This would remove the stigma attached to the word robot and also allay some of the safety fears which have held back more rapid progress.

The first attempts at producing robotic systems for the disabled began in the late 1960's and early 1970's. Nearly all these systems have failed to reach production because of problems of acceptance by the intended users due to poor design of the human/machine interface and the high unit cost. The main emphasis to date has involved research into robotic workstations (Davies, 1984; Fu, 1986; Gosine et al, 1988; Harwin et al, 1986a; Harwin et al, 1988; Kwee, 1986; Valettas, 1988) as opposed to mobile robotic systems (Kwee, 1986; Kwee & Duimel, 1988a; Kwee & Duimel, 1988b; Van der Loos, 1988).



### **1.2.2 Robotic Workstations**

These usually consist of a table-mounted robotic arm which can manipulate and/or interact with various other objects, e.g. a computer, books, feeding utensils, etc. The robot is fixed in one place and is said to be working in a structured environment, because the objects with which the robot interacts have a fixed spatial relationship with respect to the robot and these locations are stored in the memory of the robot controller. The method of initiating a task or sequence of tasks is influenced by the nature of the user's disability but is usually by a switch or combination of switches. The advantages of this type of system are that it is a self contained unit which can be situated in any convenient place within a care home, hospital or other institution and that it can be used by a group of physically disabled people on a rota basis. However, due to the high cost, many individuals who need to use such a system in a domestic environment cannot afford it. Furthermore, the disabled user generally interacts only with the objects and components that are based on the workstation.

### **1.2.3 Mobile Robots**

These consist of a robotic device mounted on a powered mobile base. The user controls the system through either long electrical cables, infra-red links, voice commands or directly, depending on the configuration of the system and the man/machine interface in use. These systems are designed primarily for use by one person in their home environment. Mobile robots work in unstructured environments under direct control of the user, therefore little modification has to be made to the layout of the home.

The use of commercial robots in workstation systems tends to increase the cost of the final system beyond the means of most disabled people (who are probably not working). This generally limits their use to people in institutional care. Since the majority of physically disabled people are living at home with support from partners and family, this is an important factor in favour of mobile systems. A robotic arm attached to an electric wheelchair and controlled directly by the user, with the ability to run pre-programmed routines, has the advantages that it is always within reach and can be manoeuvred with the wheelchair to perform a variety of tasks inside and outside the home, ie, gardening. Making use of the wheelchair's powered base would also provide the power source and help to reduce costs. If the system was required to operate outdoors it would therefore have to comply with current British and I.S.O. standards for safety, stability and climatic testing, eg BS 6935 Wheelchair Tests, ISO 7176 Parts 1-14 Wheelchairs.

### 1.2.4 Previous Work

As part of this research programme, a literature review of world rehabilitation robotics research was undertaken (Prior & Warner, 1990a) which showed that of 37 projects, 28 were investigating workstation systems whereas only 9 were researching mobile systems. This indicates a need for greater research into the area of mobile rehabilitation robots. Of the 28 workstation systems, 21 were using commercial robots whereas only 7 were using purpose-built robots. This contrasts with the mobile systems where 8 were using purpose-built robots and only 1 was using a commercial robot. It is interesting to note that of the mobile systems only two wheelchair-mounted systems, the Manus project and the Inventaid manipulator are still being researched actively. The pioneers in the field of rehabilitation robotics began their research in the late 1960's and early 1970's; two of the founders in this field, who are still active are Prof. Leifer (formerly Director of the Rehabilitation, Research and Development Center) at the Veterans Administration Medical Center, Palo Alto, U.S.A. and Dr. Hok Kwee who is the head of the Manus project based at Hoensbroek, the Netherlands. Researchers at Palo Alto are currently working on two main projects and several related projects (Leifer et al, 1978; Leifer, 1981; Editor, 1988). The two main projects are a robotic workstation, and an autonomous mobile robot. Both use the PUMA<sup>®</sup> 260 robotic arm manufactured by Unimation Ltd. The robotic workstation project is nearing completion, and is expected to cost in the region of £30,000, of which, £23,000 is the cost of the PUMA<sup>®</sup> robotic arm. The French Spartacus project, the forerunner of the Manus project, applied an existing nuclear robotic manipulator, the MA-23 to aid the disabled. This research enabled Dr. Hok Kwee to formulate the requirements of a rehabilitation robot (Kwee, 1986). The Manus project is researching into an electric wheelchair-mounted manipulator (Kwee, 1986; Kwee & Duimel, 1988a; Kwee & Duimel, 1988b; Kwee et al, 1987). It has reached the production stage. Each unit costs in the region of £25,000 and will therefore be available to only a very small percentage of the disabled population.

Several other wheelchair-mounted robotic systems have been developed in the past twenty years, notably by Spar Aerospace of Canada (Taylor, 1978), the VA Medical Center of New York (Mason & Peizer, 1978), the Jet Propulsion Laboratory of the California Institute of Technology and the University of Virginia. However, all of these systems failed to reach the production stage due to their high costs, poor user interfaces and the apparent lack of initial research into the specific tasks required by the user (see Section 2.3).

Research in the UK has been mainly directed towards the use of workstation systems. The most notable are at Bath Institute of Medical Engineering (Hillman, 1987a; Clay et al, 1987), Imperial College of Science, Technology and Medicine (Davies, 1984), and at

Cambridge University (Gosine et al, 1988; Harwin & Jackson, 1985; Harwin et al, 1986; Harwin et al, 1988). The one exception is the Inventaid electric wheelchair-mounted manipulator designed by Jim Hennequin of Airmuscle Ltd and built by the Papworth Group. This device is currently undergoing field trials at rehabilitation centres worldwide and currently retails for just under £5,000 for the basic model (Hennequin, 1991).

The most successful commercial robot to be used worldwide for rehabilitation applications is the RTX<sup>®</sup> manufactured by Universal Machine Intelligence, which is of a SCARA configuration (horizontally articulated) and which currently retails at approximately £6,000 (Colton, 1988; Faletti & Clark, 1984; Fu, 1986; Gosine et al, 1988; Harwin & Jackson, 1985; Harwin et al, 1986a; Harwin et al, 1988; Mathews, 1987; Valettas et al, 1988).

Nearly all the rehabilitation robots in existence use electric motors for their actuation systems. Hydraulic systems are generally ruled out due to their high cost, large mass, high pressure and problems of oil leakage. There are very few examples of rehabilitation robots using pneumatic actuators, despite their distinct advantages of low-cost, high power/weight ratio, compliance, compactness, cleanliness and the fact that they can operate in adverse environmental conditions (Plettenburg, 1989). Industrial pneumatic robots do exist in small numbers, however, they are nearly all controlled using physical set-up methods (Pera, 1981) based on simple vane type actuators using bang-bang control and perform tasks where fine trajectory control is not critical. In the case of rehabilitation robotics, fine trajectory control is sometimes essential to perform specific tasks. In view of the inherent advantages of pneumatic actuation, research is therefore needed to investigate, evaluate and apply new forms of actuation systems using pneumatics for rehabilitation robotic manipulators.

### 1.3 HUMAN FACTORS, ERGONOMICS AND DISABILITY

Before any detailed design specification can be written for a rehabilitation robot, a review of the general characteristics of the user population and their environment must be conducted. In view of the role of this device, research was conducted to obtain data in the following areas:

- Human factors information;
- Ergonomic data on wheelchairs and the home environment;
- Anthropometric data on wheelchair users, and
- Statistical data on disability.

### 1.3.1 Human Factors Information

Human factors engineering is the practice of designing products so that the user can perform required use, operation, service and supportive tasks with a minimum of stress and a maximum of efficiency.

The human arm is said by many to be the perfect manipulator, and one to which all such replicas should be compared (Young, 1971). A review of the human arm is presented here as a standard for comparing the performance of robotic designs.

#### 1.3.1.1 The human arm (Kapandji, 1980; Croney, 1971)

The human arm consists of the shoulder joint, (the most mobile of all the joints in the human body), which is attached to the torso, the upper arm which extends to the elbow joint, the lower arm which extends to the wrist, and finally the hand itself consisting of four fingers and a thumb (see Figure 1.1). The human arm has 7 degrees of freedom and the hand has another 14, making a total of 21 (three times that of most industrial robots).

The ranges of arm motion are given below, with the position of reference ( $0^\circ$ ) defined as that taken up by the upper limb hanging vertically downwards at the side of the trunk.

| Shoulder (Three D.O.F)         | Range  | Terminology                        |
|--------------------------------|--------|------------------------------------|
| 1. $+180^\circ$ to $-50^\circ$ | (230°) | Flexion - Extension                |
| 2. $+30^\circ$ to $-180^\circ$ | (210°) | Adduction - Abduction              |
| 3. $+80^\circ$ to $-95^\circ$  | (175°) | Lateral Rotation - Medial Rotation |
| Elbow (One D.O.F)              | Range  | Terminology                        |
| 1. $+145^\circ$ to $0^\circ$   | (145°) | Flexion - Extension                |
| Wrist (Three D.O.F)            | Range  | Terminology                        |
| 1. $+15^\circ$ to $-45^\circ$  | (60°)  | Adduction - Abduction              |
| 2. $+65^\circ$ to $-73^\circ$  | (138°) | Flexion - Extension                |
| 3. $+90^\circ$ to $-180^\circ$ | (270°) | Pronation - Supination             |

The human hand has four fingers and one thumb which together provide 14 degrees of freedom.

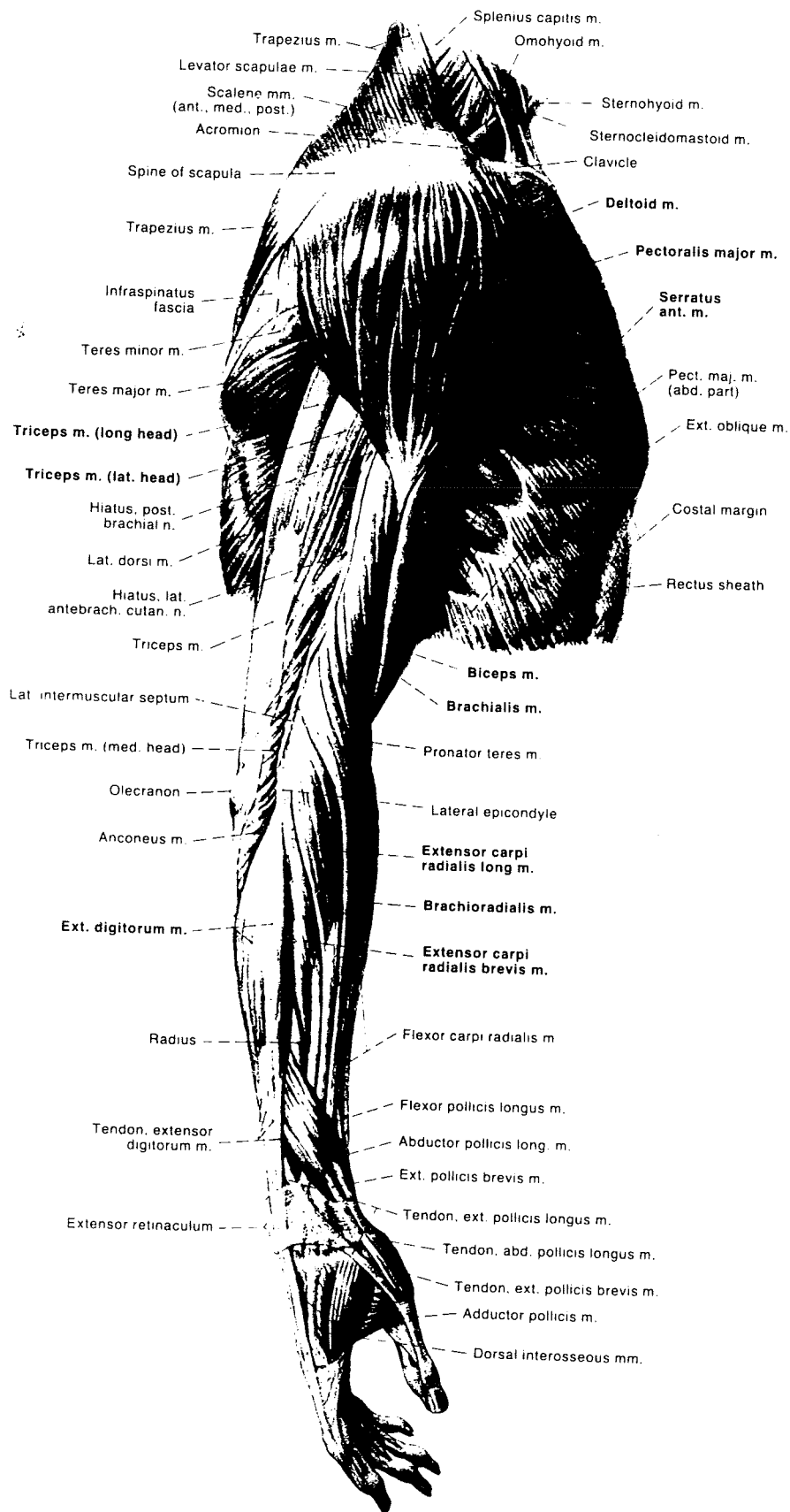


Figure 1.1 - The human arm (Clemente, 1987)

**Table 1.1 - Human Arm Performance.** (Andeen, 1988; Liu et al, 1984)  
(for the 50%ile male adult)

| Max. Reach at Wrist | Max. Payload | Max. Speed (No Load)  | Accuracy <sup>†</sup> | Upper Arm Mass‡ | Lower Arm Mass‡ | Hand Mass‡ |
|---------------------|--------------|-----------------------|-----------------------|-----------------|-----------------|------------|
| 0.54 m              | 10 kg        | 2 m sec <sup>-1</sup> | ± 0.5 mm              | 2.3 kg          | 1.5 kg          | 0.6 kg     |

† The accuracy quoted above is based on visual feedback, without visual feedback the accuracy ranges from ± 14 mm to ± 33 mm (Woodson, 1981).

‡ The body segment masses are directly proportional to the individuals body mass.

The total arm mass of the average male adult is therefore 4.4 kg, giving a maximum payload to weight ratio of 2.3:1.

**Table 1.2 - Human Arm Resonant Frequencies and Lengths.** (N-Nagy & Siegler, 1987; Diffrient et al, 1974; for the 50%ile male adult)

| Upper Arm | Lower Arm | Hand      |
|-----------|-----------|-----------|
| 10-20 Hz  | 16-30 Hz  | 50-200 Hz |
| 282 mm    | 254 mm    | 191 mm    |

The ratio of the length of the upper arm to the lower arm is thus 1.1:1 and the ratio of the arm length to the hand length is 2.8:1. These characteristics have a very significant impact on the performance and working envelope of the manipulator as shown below.

Taking the case of the perfect three degree of freedom planar robotic manipulator with ( $\pm 180^\circ$  joints), where link 1 represents the upper arm, link 2 represents the lower arm and link 3 represents the hand. It can be shown that the useful workspace can be optimised if links 1 and 2 are the same length and link 3 is as small as possible. The workspace is therefore a circular area defined from (Rivin, 1988) as:

$$\text{Workspace} = 0 \leq \sqrt{(x^2 + y^2)} \leq (2l_1 + l_3) \quad (1.1)$$

In reality it may not be possible or practical to make the first two links of the same length and therefore a compromise is reached whereby the ratio of link 1 to link 2 is 1.1:1, the same as the human arm. This will make the arm mechanically stable and will also make it aesthetically correct. The position of the centres of gravity within the human arm dictate its performance, it is important to know where these positions are.

**Table 1.3 - Centre of Gravity Positions (\*) in the Human Arm. (Diffrient et al, 1974)**  
(for the 50%ile male adult)

| Upper Arm        |        | Lower Arm     |      | Hand    |      |
|------------------|--------|---------------|------|---------|------|
| 43.6 %           | 56.4 % | 43 %          | 57 % | 28 %    | 72 % |
| *                |        | *             |      | *       |      |
| ← Shoulder Joint |        | ← Elbow Joint |      | ← Wrist |      |

From the results of the above table we can see that the positions of the C of G in both the upper and lower arms are roughly at the midpoint, whereas the C of G of the hand is situated at a position just over a quarter the length of the hand in the direction of the finger tips. This arrangement lowers the inertia of the hand thus limiting the torque experienced at both the elbow and shoulder joints.

### 1.3.2 Ergonomic Data

Information on the range and sizes of electric wheelchairs, and data on the home environment is essential when designing an electric wheelchair-mounted robotic arm to be used in the home. Due to the large number of electric wheelchair manufacturers, statistical data on specifications and dimensions is difficult to obtain. The following data is based mainly on a survey of 35 electric wheelchairs (Segedy, 1991), together with other sources (Todd, 1990).

#### Front Wheel Diameter

min - 102 mm      Mean = 222 mm  
max - 513 mm      S.D. = 60 mm

#### Rear Wheel Diameter

min - 203 mm      Mean = 445 mm  
max - 610 mm      S.D. = 138 mm

**Armrest Height**

min - 622 mm      Mean = 737 mm  
 max - 824 mm      S.D. = 24 mm

**Overall Mass**

min - 23 kg      Mean = 66 kg  
 max - 155 kg      S.D. = 29 kg

**Overall Width**

min - 476 mm      Mean = 630 mm  
 max - 711 mm      S.D. = 45 mm

**Seat Depth**

min - 254 mm      Mean = 410 mm  
 max - 508 mm      S.D. = 36 mm

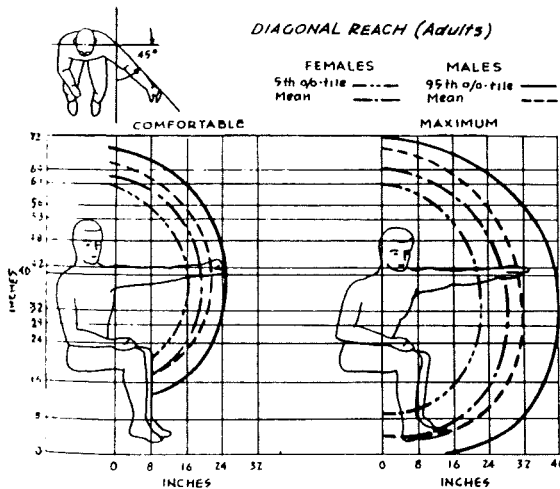
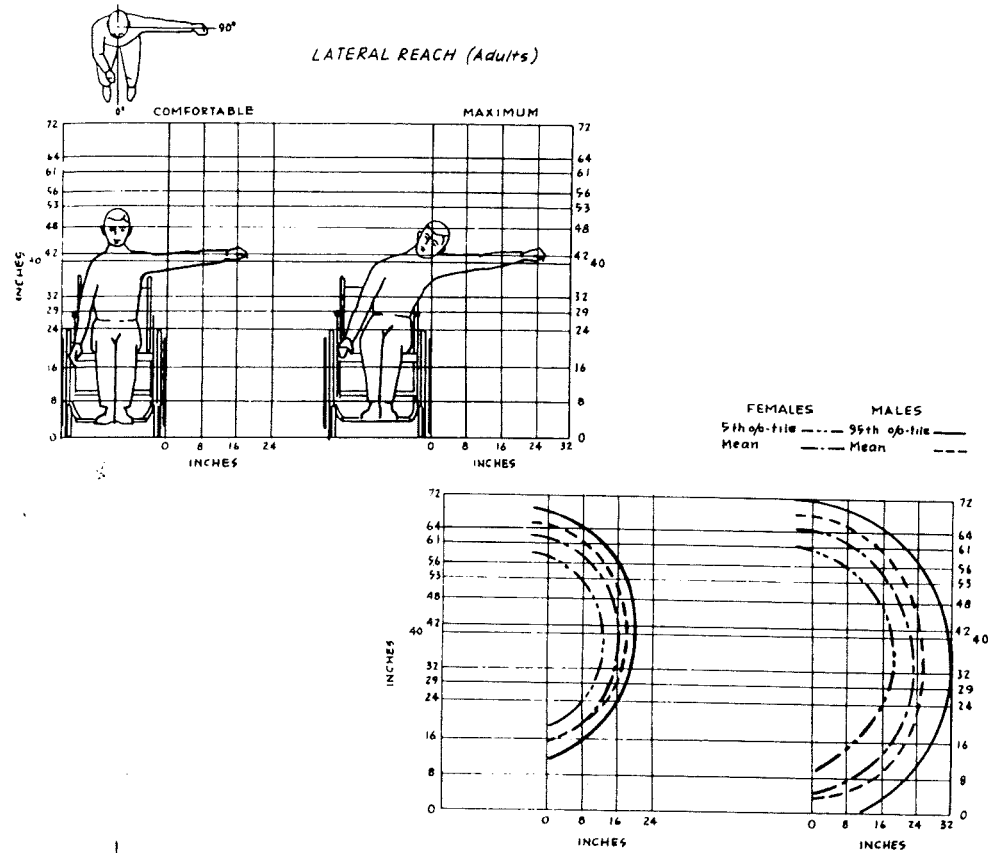
This data has important implications for the placement, design and reach characteristics of a wheelchair-mounted manipulator (see Section 4.2).

Many standards exist for the design of buildings to enable easy access for the wheelchair user (Goldsmith, 1977). For a small wheelchair, the minimum width of a doorway or corridor is 760 mm (preferred minimum 910 mm), whereas for a large wheelchair the minimum width required is 790 mm (preferred minimum 940 mm). Table top heights for wheelchair users should be between 711-864 mm from the floor level, this is to enable most wheelchair armrests to pass under the table top (Floyd et al, 1966).

### 1.3.3 Anthropometric Data

Before the design criteria for a wheelchair-mounted robotic arm can be determined, it is useful to establish the dimensional characteristics of wheelchair-bound disabled people. There has never been a specific anthropometric survey of electric wheelchair users. The only data available pertains to a study of paraplegics made by Floyd and others (Floyd et al, 1966). The difficulty in obtaining reliable data on this particular group of people is further hampered by their lack of homogeneity due to their varying disabilities (Goldsmith, 1977). Figure 1.2 shows the comfortable and maximum reach characteristics of wheelchair-bound paraplegics, ie those with upper limb mobility, based on Floyd's work. Figure 1.3 shows comparable data, with emphasis on slightly different features. The data from these sources can only be used in a general sense, since the current research involves the design of a robotic device to be fitted to powered wheelchairs and used mainly by quadriplegics. One goal of the research is to enable the quadriplegic to function as a paraplegic in terms of simple reaching, stretching and gripping tasks. In this respect it is helpful to be able to estimate to what extent paraplegics are able to reach and therefore how the robotic aid is able to replace lost function. Because of the requirement to pick up objects from the floor, tests were conducted on a Vessa Vitesse powered wheelchair to ascertain what regions of the floor were visible to the user with and without neck movement. Blind regions around the base of the wheelchair have been identified and are shown in figure 1.4. If full access to the floor, around the base of the wheelchair was required then this would mean that the





**Functional Reach from a Wheelchair<sup>1\*</sup>**

The approximate reach-limit values shown in the accompanying graphs were derived on the basis of a sample of 91 male and 36 female subjects confined to a wheelchair. Note the differences between the maximum and the comfortable reach limits, a subjective but important consideration in design.

| Male              | 5th Percentile | Mean | 95th Percentile | SD  |
|-------------------|----------------|------|-----------------|-----|
| Floor to vertex   | 49.1           | 52.4 | 55.7            | 2.0 |
| Floor to eye      | 44.7           | 48.1 | 51.5            | 2.1 |
| Floor to shoulder | 38.4           | 40.8 | 43.2            | 1.5 |
| Floor to elbow    | 24.9           | 27.3 | 29.7            | 1.5 |
| Floor to thigh    | 23.3           | 25.4 | 27.5            | 1.3 |
| Shoulder width    | 14.3           | 16.8 | 19.3            | 1.5 |
| Hip width         | 12.2           | 14.1 | 16.0            | 1.2 |
| Toe projection    | 3.7            | 5.1  | 6.5             | 0.9 |
| Lower leg length  | 15.7           | 17.3 | 18.9            | 1.0 |
| Age in years      |                | 34.7 |                 |     |

| Female            | 5th Percentile | Mean | 95th Percentile |
|-------------------|----------------|------|-----------------|
| Floor to vertex   | 46.9           | 50.4 | 53.8            |
| Floor to eye      | 42.7           | 46.4 | 50.1            |
| Floor to shoulder | 35.4           | 39.3 | 42.2            |
| Floor to elbow    | 23.2           | 26.7 | 30.2            |
| Floor to thigh    | 22.8           | 24.7 | 26.6            |
| Shoulder width    | 13.5           | 15.1 | 16.7            |
| Hip width         | 12.6           | 14.3 | 16.6            |
| Toe projection    | 2.6            | 4.1  | 5.6             |
| Lower leg length  | 14.4           | 16.2 | 18.0            |
| Age               |                | 32.1 |                 |

<sup>1\*</sup>W. F. Floyd et al. "A Study of the Space Requirements of Wheelchair Users." *Paraplegia*, vol. 4, no. 1, pp. 24-37. May 1966

**Figure 1.2 - Reach characteristics of paraplegics. (Floyd, 1966)**

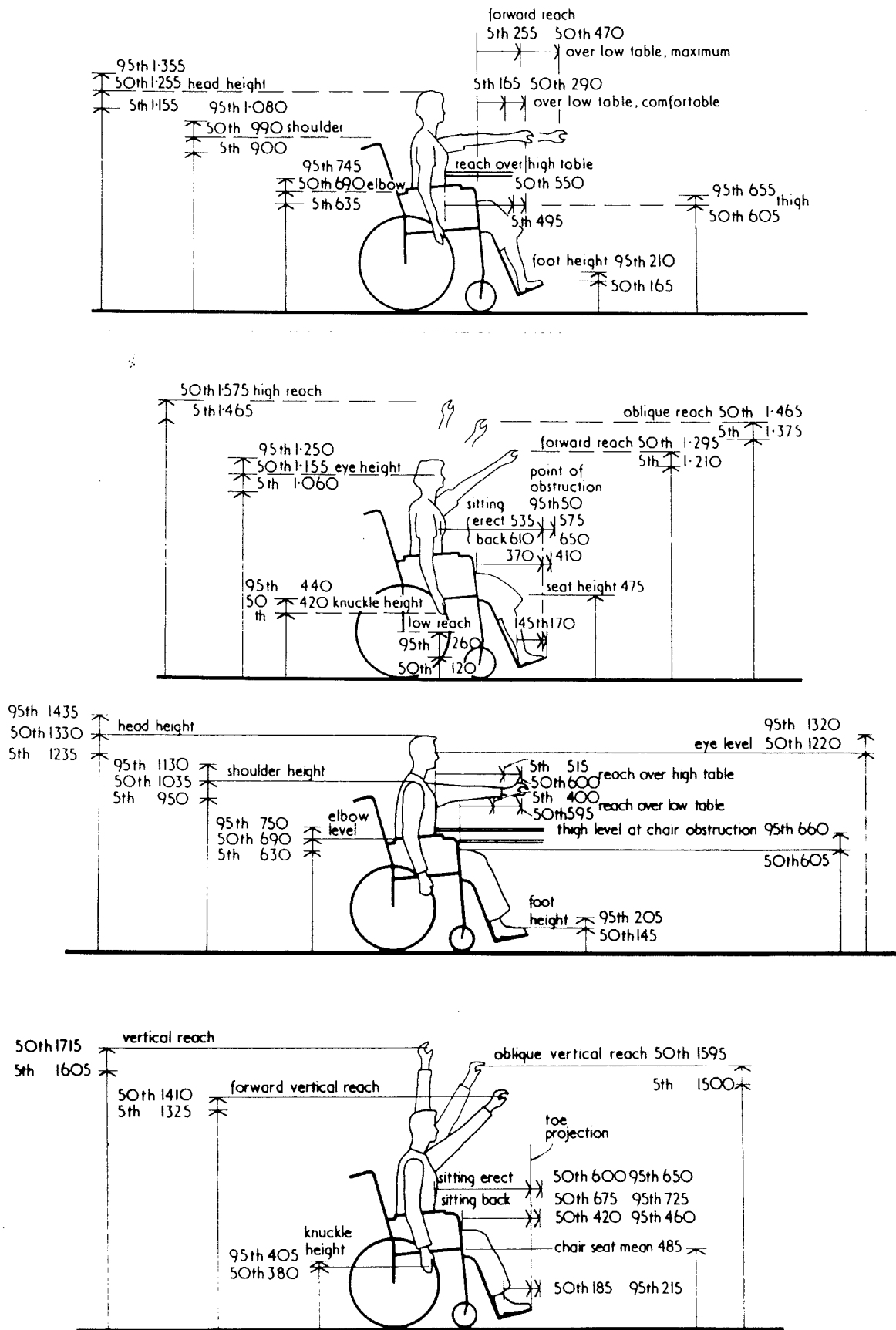


Figure 1.3 - Dimensions of adult wheelchair users.  
(Goldsmith, 1977)

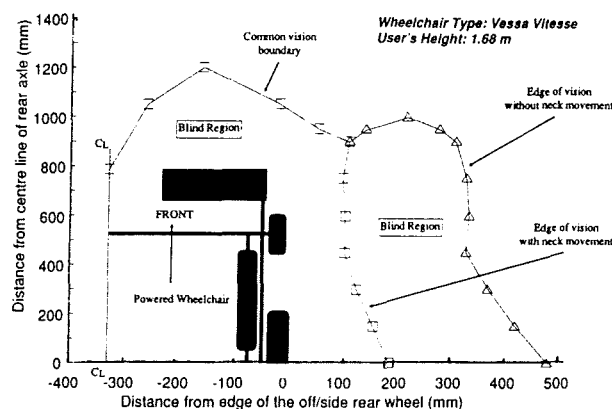


Figure 1.4 - Blind regions around the base of a vessa vitesse powered wheelchair.

robot arm's reach would have to be greater than the human arm, or just as dextrous. As a compromise solution, the robot arm should be able to reach to the floor level at a series of points, some of which are outside the blind regions.

### 1.3.4 Statistical Data

Statistical data on wheelchair users is limited. However, one of the most up-to-date and reliable sources for this information is the 1989 OPCS survey of disability in Great Britain (Martin et al, 1989). This was a national survey of the disabled carried out during the period 1984-1988. The results of the survey are based on interviews with 10,000 disabled people in private households and 4,000 disabled people in communal establishments, making it one of the largest surveys of the disabled and elderly conducted in Great Britain.

Table 1.4 - Statistics on Disability in Great Britain. (Martin et al, 1989)  
(figures in thousands)

| U.K. Population (Total) | Disabled Adults (6,202) |             | Severely Disabled (8-10)§ | Wheelchairs (Non-Powered) |             | Wheelchairs (Powered) |             |
|-------------------------|-------------------------|-------------|---------------------------|---------------------------|-------------|-----------------------|-------------|
|                         | Private House           | Comm. Est.† |                           | Private House             | Comm. Est.† | Private House         | Comm. Est.† |
| 57,000                  |                         |             | 971                       |                           |             |                       |             |
|                         | 5,780                   | 422         |                           | 400                       | 126         | 40                    | 12          |

† Comm. Est. - Communal Establishments.

§ Most severely disabled categories (8-10).

Statistics show that approximately 14.2% of adults in Great Britain are defined as disabled in some way. This level of disability compares with 13.2% in Canada (Cameron, 1988), 9.1% in the U.S.A. (D.H.H.S., 1982; excluding those in communal establishments), and has been estimated to be in the region of 500 million worldwide (Editor, 1981).

From the OPCS survey, the most severely disabled (categories 8-10) contained a total of 971,000 people, of this group 40-50% are wheelchair users. From this research the number of non-powered wheelchairs in Great Britain is therefore approximately 526,000, with about 10% of this total being powered wheelchairs. In the USA the number of non-powered wheelchairs has been estimated to be 1.2 million (Todd, 1990).

In the UK prior to 1985 wheelchairs were provided by the Department of Health and Social Security; from 1985 until 1991 they were provided by the Disablement Services Authority and are currently provided by local health authorities. Accurate estimates of the total number of privately bought wheelchairs do not exist. However, the OPCS survey found that 16% of disabled adults with a wheelchair, living in private households had bought their wheelchair privately, in most cases this was a powered model.

A recent market analysis (Finlay, 1988) of wheelchair sales stated that the estimated sales in the UK of non-powered wheelchairs was 60,000/yr and for powered wheelchairs was 20,000/yr. The principal purchasers of non-powered wheelchairs was stated to be local health authorities, whereas powered wheelchairs were more likely to be purchased by private individuals. In view of the OPCS findings, the figures for sales of powered wheelchairs must be judged with some caution. If the average life of a powered wheelchair is taken as 5 years then the sales are more likely to be in the region of 10,400/yr.

From the same survey it was stated that the projected sales of a proposed 'fetch and carry' robot costing £10,000 could be 170 units/yr (140 units to local authorities and 30 units to private individuals). This small market is highly price sensitive, but none the less attractive when compared to total UK industrial robot installations of 747 units in 1991 (Editor, 1991). Since the UK has only about 3.5% (Editor, 1984) of the world market for healthcare products, the total world sales/yr of such a system could be as much as 30 times higher.

In view of these findings there would appear to be a market for assistive robotic devices, if they are designed to fulfill the user's needs at a cost many can afford. Devices costing less than £5,000 can be considered as low-cost and are therefore likely to be purchased

outright. However, devices costing over £5,000 are more likely to be purchased by local health authorities, etc. An alternative to the outright sale might be a form of leasing arrangement whereby the users rent the equipment for as long as they require it.

It would seem appropriate therefore, that an electric wheelchair-mounted robot should be marketed as an optional accessory - available from major wheelchair manufacturers in addition to the standard wheelchair. For successful technology transfer, it is essential that links are made between research and development departments and the assistive device retailers.

## **1.4 AIM AND OBJECTIVES OF THE WORK**

### **Aim:**

The aim of this research programme is to investigate novel design and construction aspects of a rehabilitation manipulator which can perform the tasks that disabled people would most like to do, at a cost the majority can afford.

### **Objectives:**

1. To research the human factors, ergonomics, anthropometrics and statistics relating to disabled people, with special reference to wheelchair-bound individuals.
2. To review past and present work in the area of rehabilitation robotics, with special reference to wheelchair-mounted systems. From this review, analyse the approach taken by other groups and determine the best methodology and criteria for the current research.
3. To investigate and evaluate the needs and abilities of wheelchair-bound people suffering from various physical disabilities by the use of a questionnaire survey. This will involve disabled people as early as possible in the design process.
4. To rate the most important tasks, as defined by the survey subjects to form the most feasible tasks using a suitable criteria based method. The results of this method would then be ranked in order of simplicity to form a priority task list.
5. To define a design specification which combines information from the needs analysis of disabled people, together with data from the priority task list, ergonomic data, performance data from (2) and references to British and International standards.

6. To compare the performance of the flexator pneumatic rotary actuator with other forms of direct-drive actuator; pneumatic, electrical and hydraulic. To investigate the static performance characteristics of single flexators of various sizes when used in a rotary type actuator. To investigate the dynamic performance characteristics of selected rotary flexator actuators. To investigate the theory of controllable compliance when used in antagonistic flexator pairs.
  
7. To derive a theoretical analysis of the flexator system which describes the performance of the system under different operating conditions.
  
8. To simulate a single-axis arm, driven by a dual flexator rotary actuator to determine its operational limits and identify the key parameters that contribute to its performance under closed loop control.
  
9. To investigate novel kinematic arrangements of the arm structure in relation to the wheelchair-mounted setting and the type of tasks to be accomplished.
  
10. To develop a multi-axis prototype arm integrating the kinematic arrangement in (9) with the most appropriate actuator for each joint as determined from (6).
  
11. To investigate the role of pre-programmed and direct teleoperator control with reference to the priority task list.

## **1.5 PREVIEW OF THE THESIS**

In chapter 2 applications of rehabilitation robotics from fifty-six research centres covering five industrialised regions: North America, UK, Canada, Europe & Scandinavia and Japan are reviewed. The use of commercial or purpose-built robots is discussed together with descriptions and costs of systems which are commercially available. Following this, there is a detailed review of wheelchair-mounted robotic arm projects dating from the early 1970's up to the present. Specifications are given, together with design philosophy and the reasons why previous systems failed to reach production are postulated.

Investigation of the user requirements of a wheelchair-mounted robotic arm are given in chapter 3. Previous questionnaire surveys of the disabled are reviewed, and the results of a new questionnaire survey of electric wheelchair users is presented. Correlation between the results of this survey and a smaller survey conducted in Scotland is given (see Section 3.4). From the results, a link is established between the 'most important tasks' as defined by the survey subjects and the 'most feasible tasks' as determined by

the use of a criterion based analysis method. The highest scoring tasks are those which should be easiest to achieve using a rehabilitation manipulator.

The list of highest scoring tasks, along with information on human factors, ergonomics, anthropometrics and performance data from chapter 2 was used to construct the design specification in chapter 4. Included in this chapter are references to British and International standards and details of safety features which should be embodied into the design of the rehabilitation manipulator.

Chapter 5 describes pneumatic muscle type actuators and introduces the flexator rotary actuator and compares its performance with other forms of drive - pneumatic, hydraulic and electric. A theoretical analysis of the flexator is derived based on the non-steady flow energy equation and its usefulness is discussed. Investigations into the static and dynamic performance characteristics of single and dual flexator rotary actuators are presented. An analysis of antagonistic flexator pairs is used to demonstrate the theory of controllable compliance. The chapter ends with the development of an ACSL simulation program which is used to model a single-axis dual flexator rotary actuator and identify the key parameters which affect its performance.

A novel kinematic arrangement is presented in chapter 6. This is a hybrid design incorporating both the conventional SCARA horizontally articulated arm and the PUMA vertically articulated arm geometry. Chapter 7 follows the development of a multi-axis prototype arm from an initial prototype stage to a redesigned second prototype. The prototype design being based on the kinematic geometry detailed in chapter 6 and having the most appropriate type of actuator for each joint, which in turn is based on the review of actuators in chapter 5. The specifications for the prototype design are based on the design specification in chapter 4 together with some of the human factors information from chapter 1. The system has positional feedback from the first four joints, enabling an Intel 8051 based microprocessor, which uses an assembly language program to control four reprogrammable memory locations, joint velocity and position monitoring. A proportional error based control algorithm is proposed as an initial form of simple control.

Finally, the conclusions and recommendations for further work are presented in the last chapter of the thesis.

# Chapter 2

## WORLD REHABILITATION ROBOTICS RESEARCH

---

*'My observation of watching what has happened in rehabilitation, along with other robot activities, is that it has been heavily repetitive. Certainly not without exception, but it seems to rise to the same level of incompetence.'*

*Joseph F. Engelberger, 1990.*

---

### 2.1 INTRODUCTION

The above quote, taken from the keynote address to the International Conference on Rehabilitation Robotics (ICORR '90), was qualified by Joseph Engelberger who went on to say that it was not because people of good will did not exist, nor was it because there are no brains being applied. The reason, he suggested, was that there was never enough funding and in addition to this, there was a lack of continuity (Engelberger, 1990).

As stated in Section 1.2, rehabilitation robotics covers a very diversified area of research, encompassing fixed and mobile robots as well as prosthetics, orthotics and control engineering, amongst others.

The diversity of research meant that very little detailed information pertaining to the number of researchers or the type of research in a certain area existed. The 'state of the art' in any one discipline was also unclear. The need to know where original forms of research could be conducted, prompted the author to conduct the first detailed review of world research in rehabilitation robotics.

A detailed review of world rehabilitation robotic research (Prior, 1989) was therefore undertaken as part of the research programme. This chapter presents the results of the world survey together with a detailed analysis of wheelchair-mounted robotic research.



## 2.2 A REVIEW OF WORLD REHABILITATION ROBOTICS RESEARCH

The objectives of this review were to establish the number of research centres active in the rehabilitation area and to categorise the type of research being conducted. Several reviews of rehabilitation robotics research projects have been conducted in the past, (Fengler, 1988; Harwin, 1986b; Hillman, 1987b; Jackson, 1987; Jones, 1988; Korba, 1989; Leifer, 1981) though none is as comprehensive as the one described here. The review was conducted by collating and reading any paper, journal article or conference proceedings relating to rehabilitation robotics and from interviews with researchers attending international meetings, from rehabilitation newsletters and other published reports.

World statistics from the International Federation of Robotics shows that Japan has 58% more industrial robots in use (274,000), than the rest of the world put together (174,000).<sup>1991</sup> However, the U.S.A. together with the United Kingdom and Canada are the leading countries in the field of rehabilitation robotics research, this is mainly due to the fact that Japan concentrates its efforts on manufacturing, where it leads the world in industrial robot applications.

From the review, fifty-six research centres were identified from five industrialised regions, which have been active in the area of rehabilitation robotics research.

These regions were:

1. North America (28 centres)
2. United Kingdom (13 centres)
3. Canada (8 centres)
4. Mainland Europe and Scandinavia (5 centres)
5. Japan (2 centres)

### 2.2.1 Rehabilitation Robotics Applications

The term rehabilitation robotics covers a wide range of different applications. For the purpose of this review the activities of the research groups have been divided into three main areas, these are:

1. Workstation robots
2. Mobile robots
3. Other applications - prosthetics, orthotics, etc.

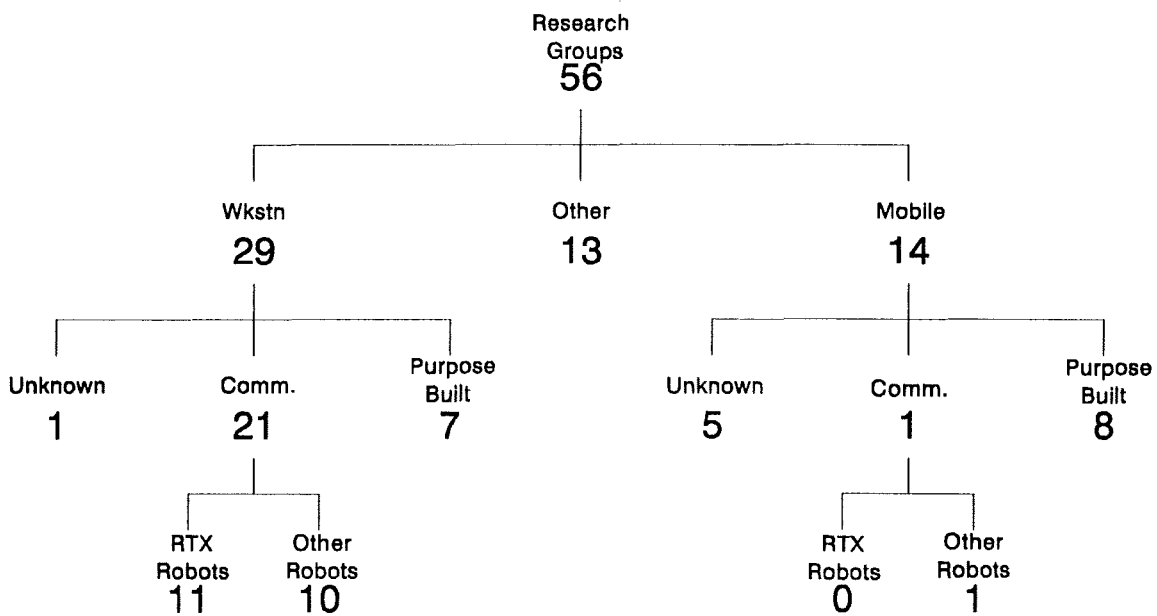


Figure 2.1 - World rehabilitation robotics survey.

The first two areas were then further sub-divided into those using commercial or purpose-built robots. The commercial robot sections were then divided into those using the RTX robot manufactured by Universal Machine Intelligence, London and those using robots from other manufacturers.

The results of the world review are summarised in figure 2.1 above.

### 2.2.2 Discussion of the World Review

Figure 2.1 shows that over twice as many research projects involve robotic workstations as compared to mobile robots. The reasons for this are that generally speaking workstation systems are easier to design in terms of space, weight and power requirements. They also have the inherent advantage that they can be operated by a group of disabled people on a potentially cost effective rota basis. Because of the problems of space, weight and power, mobile systems tend to have purpose-built robotic arms whereas workstation systems utilise commercially available robots. Commercially available robots are primarily used in workstation systems and operate in a well structured environment. This factor coupled with the selection of a robot of proven reliability gives them a higher chance of success of achieving a limited range of tasks.

The advantage of designing purpose-built robots is that the needs of the end user can directly influence the final design of the device and the tasks that it can meet. There will always be a place for both types of systems because there will always be cost constraints

placed on research projects in this area. The choice of purpose-built or commercial robot can have a great effect on the cost and time scale of the project. Purpose-built robots have the disadvantage of increasing the time before the system is fully implemented, due to the time needed for design and manufacture.

Research projects in the USA have a high ratio of 4:1 in favour of workstation systems as opposed to mobile systems, whereas most of the other countries in the review tended to have a more balanced ratio of 1:1 between these two systems. This may in some part be due to the American attitude that cost is not such an important criteria when designing rehabilitation systems; with the view that the cost benefits of replacing care assistants with robotic devices can justify their high initial cost.

Observation of the commercial robot field shows that the RTX robot is one of the most popular rehabilitation robots, used worldwide in eleven workstation projects (20% of the total number of projects). The reasons for this success lies in the relatively low cost and flexibility of the system. This robot has successfully bridged the gap between educational and industrial robotics.

At present very few rehabilitation robotic systems are available to the general public. The systems that have been available the longest were developed in the USA and Canada, one of which is an autonomous mobile robotic platform, (manufactured by Transition Research Corporation under the direction of Joseph Engelberger), which is called Helpmate and retails for approximately US\$42,000 (1990 price) and has been designed as a fetch and carry tool within a hospital setting. The system can travel through corridors avoiding collisions with stationary and moving objects, it can also enter lifts. The other is a workstation system developed in Canada which is called M.O.M. (Machine for Obedient Manipulation) and has been designed to operate computers, help with feeding and as a general pick and place tool. The system retails for CAN\$15,000 (1990 price) and is available through the Neil Squire Foundation, Vancouver. In the UK, the Handy 1 robotic aid to eating, developed at Keele University and the winner of the 1992 IEE prize for helping disabled people, is one of the few systems commercially available. The system consists of a low-cost educational robot mounted on a mobile base, with a spoon type end effector. To date eighty systems have been provided for use by severely disabled people, on a regular basis. The majority of these people are suffering from Cerebral Palsy, which was the primary target group (Topping, 1992).

The Manus arm and the Inventaid manipulator are two commercially available wheelchair-mounted systems which have recently been introduced at selected test sites around the world, these retail for approximately £25,000 and £5,000 respectively (1992 prices). Both systems are reviewed in Section 2.3.

## 2.3 A REVIEW OF WHEELCHAIR-MOUNTED ROBOTIC ARM PROJECTS

The field of wheelchair-mounted robotic research is an extremely specialised area and therefore has a limited amount of background material and history on which to base valid assumptions and conclusions.

A literature review of the last twenty-five years has exposed only eight major projects, four being still active. Of these, one is a high-cost solution, the Manus arm, one is a low-cost solution the Inventaid manipulator, and of the other two, one is a proposed development of a workstation based system and the other is a new project.

The project reviews which follow will give the reader a sense of the ancestral line within rehabilitation robotics. Where one project fails, another group will usually take what is left and try to develop it further.

There is a lot of contact between members of this small community, which is good in that knowledge and experiences are shared, however, it is also detrimental because the same work and the same mistakes are repeated by several groups.

### 2.3.1 V.A. Rehabilitation Engineering Center, USA (Mason & Peizer, 1978)

In the early 1970's a project began at the V.A. Rehabilitation Engineering (formerly Prosthetics) center to design an electric wheelchair-mounted telemanipulator arm. The system consisted of a four degree of freedom (three revolute, one prismatic) arm, with a modified two finger prosthetic hook for a gripper. The maximum speed of the arm was 1 m/s and the minimum speed was 0.001 m/s. The arm was capable of lifting 2 kg anywhere in its 2.5 m diameter spherical working envelope with a maximum linear error of 25 mm. The mass of the arm was just over 20 kg and it could operate for 16 hours per day with a wheelchair range of 15 km. The arm was capable of reaching to the floor as well as to a high shelf. User control was provided by a two degree of freedom chin operated joystick and a five position mode selector.

End point velocity control was chosen, with the user providing visual feedback. A projected image showed the user in which mode the arm was working. The system was a true teleoperator without the ability to perform preprogrammed routines. The system was of high quality and well designed in terms of ergonomics, but was aesthetically poor (see figure 2.2).

However, after ten years of funding, estimated to have cost over \$100,000 the project has ceased with no practical results.

The reasons for the failure of this otherwise model project seem to be that at the

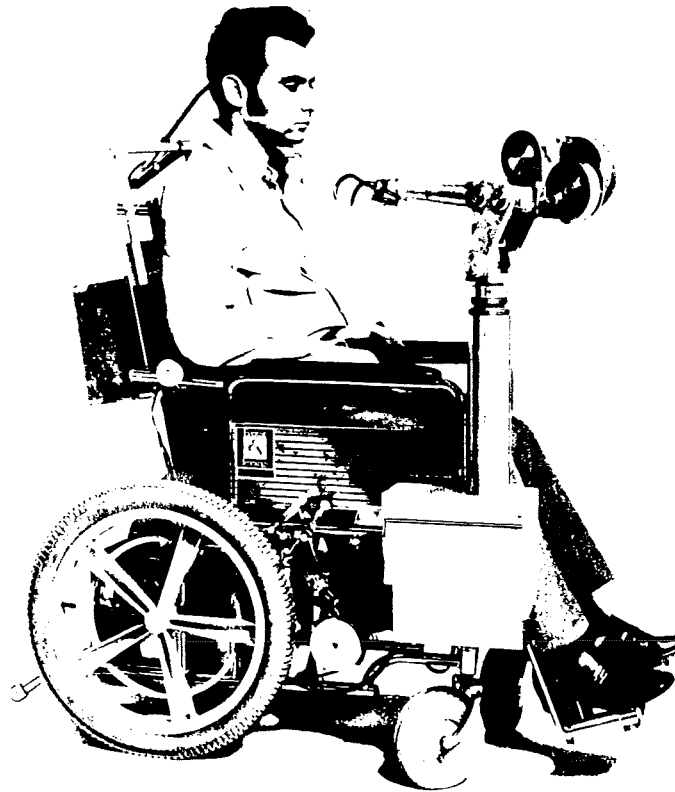


Figure 2.2 - VA rehabilitation engineering center arm c.1974

beginning of the project little or no attention was paid to the real needs of the proposed users of the system, in terms of the tasks that they would want to perform. The system had no ability to be preprogrammed, placing a heavy burden on the user. It may also be true that the type of control system used was not acceptable or appropriate for the majority of users. Another criticism was that the prismatic joint, which extended the end effector, was so long and slender that it tended to whip like a fishing rod when the arm was stopped suddenly.

In the mid 1970's, a company called General Teleoperators used the same basic design adding two degrees of freedom (five rotation, one translation). Several research teams used this manipulator in their rehabilitation projects, these included the NASA Jet Propulsion Laboratory (JPL) of the California Institute of Technology (CalTech) in Pasadena. They used this arm in 1975 for a wheelchair-mounted manipulator (see figure 2.3). The system was controlled using a 36-word voice recognition system, this was however found to be unreliable (with only a 69% recognition rate), and its speed of operation was found to be too slow. Another group which used this arm with voice control was the University of California at Santa Barbara. All the above attempts have failed because of the problems associated with early voice recognition systems and the lack of computer augmentation for preprogrammed routines.



Figure 2.3 - NASA Jet propulsion laboratory arm c.1975

Other work of interest has taken place at the Institute of Rehabilitation Medicine, New York University Medical Centre involving the design of assistive robotic devices and other aids for disabled people.

### 2.3.2 Spar Aerospace/Ontario Crippled Children's Centre, Canada. (Taylor, 1978)

This collaborative project between the Ontario Crippled Children's Centre (O.C.C.C.) and Spar Aerospace, (designers of the Space Shuttle's Remote Manipulator System) started in November 1976. The project was to be conducted over a three year period. The initial conceptual model consisted of a very simple manually operated, four degree of freedom arm of tubular construction. The arm was operated by an able-bodied technician, and gave insight to produce a preliminary design specification as follows:

- Reach objects within a 0.76 m radius of the wheelchair tray;
- Grasp and manipulate objects of up to 4.5 kg;
- Open doors;
- Operate wall switches;
- Permit eating and drinking tasks;
- Reach down to the floor;
- Accept interchangeable end effectors;
- Have a park position no higher than the arm rest, and
- Provide 0.3 m of vertical movement.

The first prototype arm design consisted of a five degree of freedom arm, based on the conceptual model but with the addition of wrist roll. The arm elevation and extension were designed to be telescopic joints, but these type of joints caused many problems in terms of drive complexity, lack of bending stiffness and restricted reach.

In September 1977, Spar Aerospace received the Phase I contract from the O.C.C.C. and started the redesign process. The design team worked with a disabled person who was employed as a psychologist by the O.C.C.C. The goal of a floor reach capability was soon dropped, but the emphasis on aesthetic design was maintained. In October 1977 Spar Aerospace received a contract from the University of Virginia for a modified version of the arm. The modifications involved the addition of potentiometric feedback on all the joints, a backdrive capability and a mechanical/electrical interface for the University's design of end effector. The University then conducted their own research programme involving computer augmented control.

The O.C.C.C. arm was mounted onto an Everest & Jennings 3P electric wheelchair (see figure 2.4). The payload requirement was reduced to 2.3 kg. The final design of the arm was machined out of Aluminium and had an overall mass of 23 kg. The elevator drive consisted of a slightly modified 12 v vehicle windscreen wiper motor. The elevator mechanism consisted of two equal length arms, set one above the other, coupled by a parallel linkage system. This allows 0.55 m of vertical travel, from park position to user

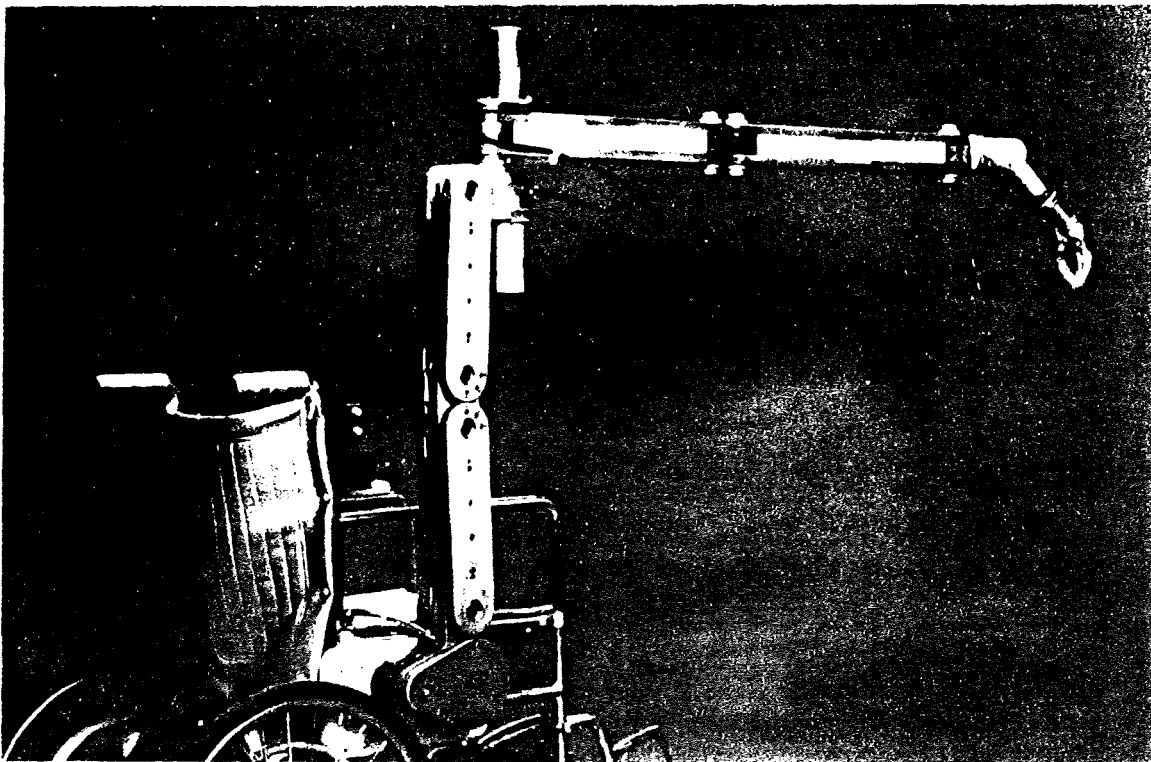


Figure 2.4 - Spar aerospace/O.C.C.C. arm c.1977

eye level. The horizontal arm consisted of the same basic geometry as the elevator section, permitting an extension/retraction range of 0.86 m. Situated at the end of the arm was a prosthetic wrist and hand assembly.

The reason for choosing the prosthetic design of wrist and end effector was stated to be, 'an expedient in a tightly scheduled program.' The arm was capable of making an azimuth traverse of 270° at and above a height of 0.79 m, from limiting positions (clearance for the wheelchair).

The interface for the arm consisted of a modified joystick with T-bar grip incorporating push button switches. Modifications and redesign continued well into 1979 culminating with a field trial stage.

The project although well researched, engineered and constructed, lacked the designers touch in terms of product design. Hampered by engineering problems and lack of funds the project ended before a production stage could be reached.

### 2.3.3 University of Virginia, USA (Ramey et al, 1980)

Researchers at the Rehabilitation Engineering Center developed an Intel 8748 microprocessor based control system for the five degree of freedom arm originally designed and built by Spar Aerospace/O.C.C.C. The project involved the design and development of a combined wheelchair and manipulator control system which allowed control of either the wheelchair or the manipulator by the use of only one input device.

The goal of the project was achieved by allowing the user to select and control two degrees of freedom simultaneously using a conventional joystick. The user changes between controlling different joints by selecting a mode change switch mounted at the users shoulder.

In order to control all seven degrees of freedom (two on the wheelchair and five on the manipulator) the control system employed a five tier operating system. Level (1) is the wheelchair mode with levels (2) to (5) for the manipulator control:

- Manipulator arm azimuth and radius;
- Manipulator arm elevation and radius;
- Manipulator arm elevation and azimuth, and
- Hand-wrist rotation and grip.

The duplication of motion control was meant to minimise the amount of level switching required, but inevitably caused confusion to the user. A VDU was used to indicate to the user what level they were on.

The prototype system was mounted onto an Everest & Jennings 24 v electric wheelchair and was demonstrated at a conference on rehabilitation technology in 1979 (see figure



2.5). Plans were outlined to redesign the control system to include a dedicated microprocessor for each of the five motorised joints, these could then be used for digital control. This would have increased the flexibility and safety of the system, but would have also increased the cost. This project relied too much on the control system design, to overcome the failings inherent in the original mechanical design and this is probably the reason why the system never reached the production stage.

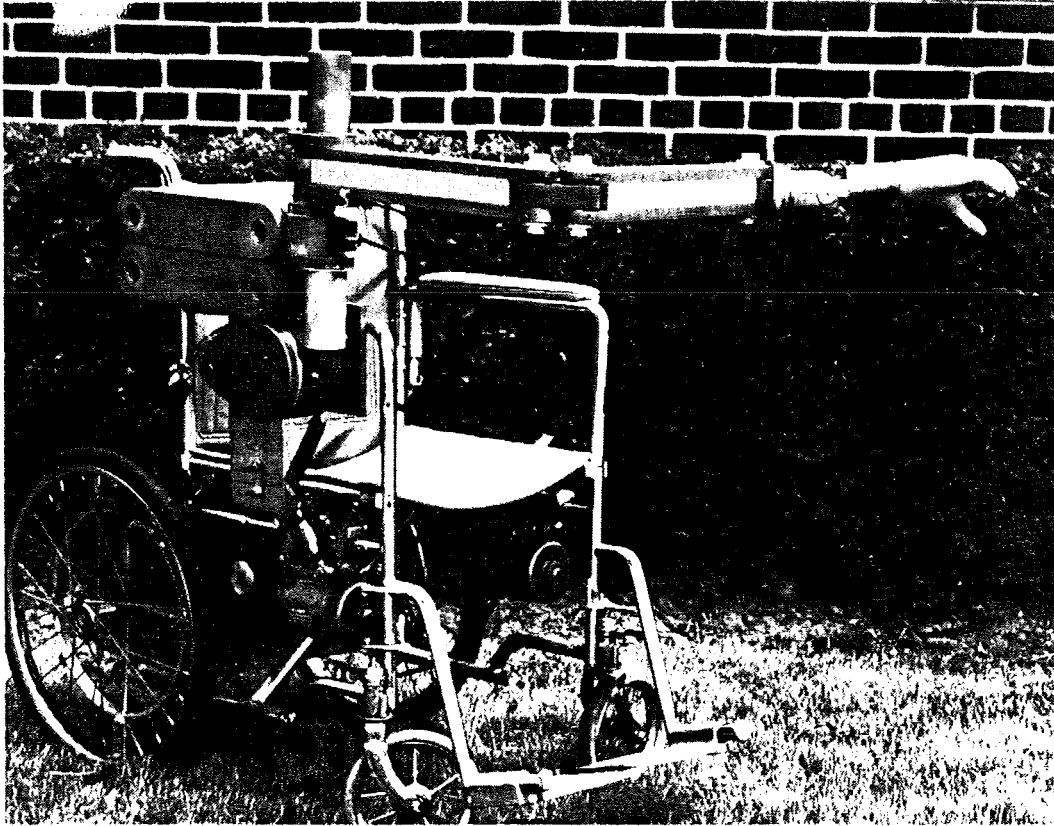


Figure 2.5 - University of virginia arm c.1978

#### 2.3.4 Zeelenberg/New Jersey Medical School, USA (Zeelenberg, 1986)

A private initiative was started in 1982 by Dr. A.P. Zeelenberg to provide a wheelchair-mounted robot for his son who was suffering from Muscular Dystrophy. An educational robot, the Cobra-RS1 was the first robot used in this experiment, the microprocessor was removed and in its place a direct control system was installed. The arm was mounted to the front left-hand corner of the users wheelchair tray. With this device the user was able to feed himself, pick and place small objects and also use it as a page turner. It is reported that because of the user's motivation, the learning curve was very short.

Although this crude and simple device allowed the user a degree of autonomy, there were many tasks that were still impossible to achieve, ie dressing, washing, preparing

food, etc. Many problems were encountered with the Dutch healthcare service regarding eligibility for a grant to purchase a robotic manipulator aid, the reasons for the delays were largely political but there was also a degree of ignorance and techno-fear.

Many important lessons were learnt from this research project, namely:

- Users want the robot arm mounted on their wheelchair;
- Users want to keep the area to their front clear of obstacles;
- An auxiliary gripping device or clamp is desirable;
- High force, large reach and increased speed are necessary when the user becomes more proficient;
- The possibility of storing memory locations is advantageous;
- Repetitive programs, such as for stirring, are important;
- Interrupts for manual 'fine control', are required, and
- Simultaneous control of more than one joint is needed.

Individuals with Duchenne Muscular Dystrophy have residual finger movement until the very late stages of the disability, therefore the simple push button type of controller is particularly suitable.

A later clinical review (Bach et al, 1990) reported the use of two robot manipulators, the Cobra RS2 and the Microbot 453-H, with six patients. The average age of the users at the start of the program was 21 years and the average use was 8.6 hrs/day. The robot arms had six degrees of freedom including grip, and were mounted to the wheelchair's lap board. They had a reach of between 0.44 m to 0.48 m, load capacity of greater than 0.45 kg at full extension, gripping force of approximately 13 N, max velocity of 0.18 m/s and weighed less than 9 kg.

Five manipulators were used in the study, two Cobras and three Microbots. The Microbot cost US\$3,500 and the Cobra cost US\$4,500 (1986 prices). Modifications were made to the control panels to make them smaller and the buttons were replaced by a touch sensitive pad. The interface was tailored to the needs of the individual user, hence the need for modular interfaces which can be quickly interchanged without delays. Initially no changes were made to the robot mechanics except that the gripper fingers were fitted with soft rubber strips to enable gripping of objects that had uneven surfaces, later, improvements were made to the range of certain joints. The users quickly adapted to this new technology, typically taking two weeks to become proficient.

The three most important uses for the robot were:

- Assistance with eating;
- Manipulation of remote and environmental control systems, and

- Recreational activities.

Recreational activities involved model making, playing cards and other hobbies. Attendant time saved by using the robot was estimated to be an average of 3 hrs/day/person. The results of this later study are particularly important as they were conducted with patients referred to the University Hospital, New Jersey Medical School, USA, and the Vereniging Spier Ziekten, Amstelveen, the Netherlands, over a period of 1 to 6 years (average of  $3 \pm 1.8$  yrs per patient) making it one of very few long term clinical studies.

### 2.3.5 The Institute for Rehabilitation Research, Hoensbroek, the Netherlands

Following a one-year feasibility study, the Manus project officially started in 1984 with funding for a two to three year period as a collaborative effort between four research and development institutes, these were:

1. Institute for Rehabilitation Research;
2. Institute for Applied Physics - TNO;
3. TNO Product Centre, and
4. Netherlands Institute of Preventative Medicine.

The feasibility study derived the basic specification of the manipulator and concluded:

- The manipulator would be more useful if it were wheelchair-mounted;
- The manipulator must be aesthetically designed;
- The manipulator must have an inconspicuous park position;
- It must be able to reach to the floor and high shelves, and
- It must be able to lift books and open doors.

However, there was no consensus on the priorities of these requirements. The final design was that of an eight degree of freedom wheelchair-mounted manipulator including end effector. This had a telescopic base to move the arm in a vertical displacement of up to 0.25 m (see figure 2.6). The manipulator has a reach at the gripper of approximately 0.85 m and can lift up to 1.5 kg. The three degrees of freedom at the wrist allowed continuous rotations of the gripper. All the motors and gearboxes are mounted within the vertical column to reduce inertia, the drive is transmitted through belts, gears and concentric shafts. The use of materials such as aluminium and carbon fibre have helped to reduce the overall weight to under 20 kg but have not helped with reducing the costs. The system has a two-fingered gripper with the ability to increase the gripping force up to a maximum of 15 N. In 1989 the first prototype was successfully



Figure 2.6 - The manus manipulator c.1988

tested by a person with Duchenne Muscular Dystrophy (Kwee et al, 1991).

A business plan was produced and a production company, Exact Dynamics/Ingenium, was formed which produced a batch of fifteen production models in 1991. These first systems were sold to test sites mainly in France and the Netherlands, but also to the Hugh MacMillan Rehabilitation Centre, Toronto, Canada and the Alfred I. duPont Institute, Wilmington, USA.

Target sales after two years were predicted to be fifty units per year, with the final system estimated to cost approximately £25,000. At the end of 1992, the Manus User Group (M.U.G) was formed to coordinate feedback from the users of the initial batch.

### 2.3.6 Bath Institute of Medical Engineering, Bath, UK (Pullin, 1991)

The engineering specialists at Bath Institute of Medical Engineering have been involved with designing electrical and mechanical aids for hospitals and disabled people for many years.

This current project involves applying existing robotic technology to produce a relatively low cost robotic workstation for the severely disabled. The initial stages of the project began in 1985 with a questionnaire survey of 42 severely disabled people in and around the Bath area. This highlighted important data on the breakdown of the disabled population in terms of age, sex, type of abode, employment, etc. Included in the survey was a detailed study of the disabled persons daily needs and abilities. These results helped to identify the type of assistive device that was required and the level and type of user interface that was most suitable.

A prototype system was subsequently constructed around a five degree of freedom commercially available Atlas robotic arm. The Atlas was mounted on a 1.7 x 0.9 m mobile desk/trolley with the task modules arranged in a semi-circular arrangement. This was dictated by the spherical working envelope of the robot. The robot was interfaced to a BBC micro-computer via a purpose built interface. Control of the robot was via a two switch menu scanning system. The robot can be driven by direct control or by preprogrammed routines.

This system has undergone successful user trials at the Duke of Cornwall Spinal Unit at Odstock Hospital, Salisbury. Feedback from the user trials highlighted certain disadvantages with the Atlas arm, ie, size, noise and working envelope.

It was therefore decided that a purpose-built robotic arm would be designed and incorporated into a new system based on the original concept but using a smaller desk/trolley of 1.4 x 0.76 m. The new manipulator is of a SCARA configuration and its vertical axis is driven by a 30 W dc servo motor, with the three main rotary actuators being driven by 6 W servo motors. Optical encoders are used to sense position and it is intended to incorporate proximity and force sensors into the gripper. The wrist has both yaw and roll. It has been decided that wrist elevation is not required due to the arrangement of all the tasks in a rack at the back edge of the desk. The payload of the arm is 2 kg and it's predicted selling price is £5,000 (1991 price). The final system underwent a series of successful field trials at spinal injuries centres in the UK.

A suggested variation on the workstation-mounted arrangement, is to mount the arm onto an electric wheelchair (see figure 2.7 overleaf). This arrangement would allow reach down to a low table but would not be able to reach down to the floor level. The conceptual design allows the arm to fold up and park away behind the wheelchair. A full scale mock-up has been built and tested with wheelchair users, gaining very favourable responses.



Figure 2.7 - Bath institute of medical engineering's conceptual arm (c.1991).

### 2.3.7 Inventaid Wheelchair Manipulator, Cranfield, UK (Hennequin, 1991)

This is a collaborative project started in 1986 between Jim Hennequin, Airmuscle Ltd and Dr. Robin Platts, Director of Orthotics at the Royal National Orthopaedic Hospital, Stanmore.

The aim of the project is to develop a wheelchair-mounted manipulator for use by quadriplegics, utilising the flexator pneumatic muscle actuator and its associated technologies. The flexator, invented by Jim Hennequin is claimed to be a proportional actuator driven by compressed air. It was designed to mimic human muscle and was used originally on the now famous Spitting Image puppets to enable them to be computer controlled and give them the human-like quality of compliance.

The first system to use the flexator was a two function wheelchair-mounted arm support used by a person with Muscular Dystrophy. The system proved very successful in allowing the operator to perform certain tasks, such as feeding and painting. After four years of development work and many prototype stages the design was licensed to Papworth Industries of Cambridge, UK to manufacture six production models, three for the UK and three for export abroad. The three UK models went to the Keep Able Foundation, Southport Spinal Injuries Unit and the Royal National Orthopaedic Hospital, respectively. The fourth was supplied to Permobil (the Swedish electric

wheelchair manufacturer) for attachment to one of their wheelchairs. The fifth unit went to France and the sixth to Spain. The cost of the basic arm was just under £5,000 (1992 price).

The production model's design consists of an anthropomorphic structure, akin to the human arm. The seven degree of freedom arm including end effector, utilises the flexator actuator on all but the main arm lifting joint which is driven by a Warner telescopic electric drive (see figure 2.8). The arm can reach to the floor and to the user's face height, and can lift up to 2 kg.

Together with the work on the arm, the designer has been developing a palatal tongue controller which would allow the most severely disabled to use the system.

### 2.3.7.1 Evaluation of the inventaid manipulator

The design philosophy of the Inventaid manipulator can be summarised below, it should:

- Fold neatly to one side of the wheelchair to allow it to pass through a doorway;
- Be able to reach down to the floor and up to cupboards and door handles;
- Match human motor control the arm should be roughly anthropomorphic;
- Perform for at least two years without a service;
- Be easily repairable by a hospital technician;

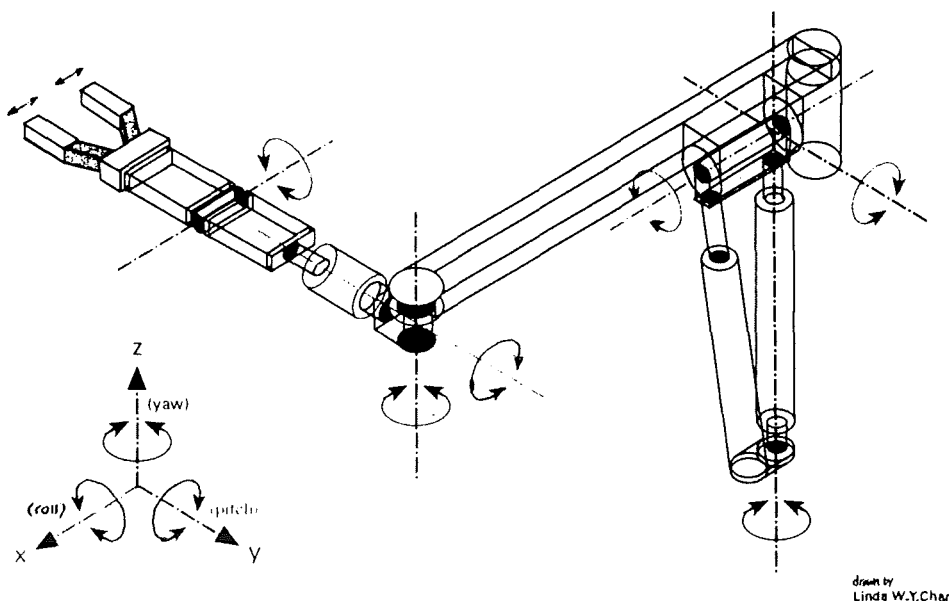


Figure 2.8 - Inventaid wheelchair-mounted manipulator c.1992

- Adapt to vehicle restraint systems;
- Be environmentally clean;
- Be silent in operation;
- Be able to be attached to a wide range of wheelchairs, and
- Fold to fit into cars.

The major joints of the arm are powered by a double-acting flexator actuator. This actuator provides smooth and controllable movement for a fraction of the cost of conventional electric or hydraulic devices, and is especially suitable for use in systems which operate in close proximity to humans, due to its compliant nature.

#### 2.3.7.2 *Aesthetics and ergonomics*

The Inventaid arm has been designed to be as aesthetic as possible. The design of a robotic device to be fitted to, and carried at all times by an electric wheelchair is a very difficult problem, not only do the designers have to consider the functional criteria such as:

- Maximum payload;
- Workspace;
- Speed of joint movements;
- Mass of arm;
- Stability, and
- Control system design,

but they must also consider the ergonomic/aesthetic design criteria such as:

- Unobtrusive park position;
- Length/Width of wheelchair not increased;
- Does the arm look good, and
- Will the user want to buy it ?

#### 2.3.7.3 *Human computer interfaces (H.C.I.)*

The designer of the Inventaid manipulator has developed several types of interface, to cater for the wide range of disabled users of the system. To date two main types of H.C.I. are currently used and a third is under development.

The first H.C.I. to be developed (and still used in the current system) is the simple push button control pad. This consists of twenty push button switches which control all the functions of the arm and end effector, together with an on/off switch.



The second H.C.I. consists of a modified joystick with 32 possible switching positions (4 x 8 switch gate). This H.C.I. operates with an LED map fixed to the arm so that the user can see which mode of operation he/she is working in.

The third and possibly the most interesting development is the palatal tongue controller. This system consists of a thin dental plate fitted to the upper teeth against the roof of the mouth. Within the plate is embedded a miniature transmitter which is operated when the tongue touches small stainless steel pads on the surface of the plate. The transmitter is energised by a radio signal at 2 MHz transmitted from a lightweight coil worn around the users neck. When the tongue makes contact with one of the steel pads, the impedance of the circuit changes and a signal is transmitted to the main coil and from there to a separate processor mounted on the wheelchair.

The palatal tongue controller is not currently available but is due to reach the market towards the end of 1993. This form of H.C.I. will have a direct benefit to both the disabled and non-disabled communities. Possible job opportunities for the disabled would then exist in computer aided design, desk top publishing, word processing and virtual reality applications.

#### *2.3.7.4 Critical analysis of the control pad H.C.I.*

Although extremely functional and practical, the push button control pad is very un-ergonomic in terms of design. The control keys are laid out in a systematic fashion rather than tailored to the needs of the user, or those of the most used tasks.

Distinction between the keys is only possible by close visual inspection, and the possibility of selecting the wrong key is high. As the user of this type of system is less able to adapt, because of their disability, it is essential that the layout of the control pad be more ergonomically designed and work on this is underway.

The reasons for choosing a push button controller in preference to other more sophisticated forms of input device are:

- Ease of installation;
- Low cost;
- Ease of modification, and
- Very reliable.

The limitation of the next cheapest interface, the joystick, is that it is used to control two or three degrees of freedom at most, whereas the arm has six or seven degrees of freedom.

One suggestion for improvement would be an interface combining the joystick principle together with a series of push buttons, similar to a computer games controller. This would enable the user to switch between modes thus he/she would be able to control up to two joints of the arm at any one time (this is more than enough, from a cognitive burden viewpoint).

The Inventaid manipulator although crude in operation has proved itself to be an easy to use and effective device for simple manipulation tasks. At 20% of the cost of it's only real competitor, the Manus arm, it should gain a large part of the wheelchair-mounted manipulator market.

### **2.3.8 The Alfred I. duPont Institute, Delaware, USA (Rahman et al, 1992)**

Researchers at the Applied Science & Engineering Laboratory are investigating a number of projects involving rehabilitation robotics. These include:

- Human factors in analogue robot control;
- Hybrid force/position control studies, and
- Low degree of freedom wheelchair-mounted robot for children.

The first project involves researching the human factors issues involved in the direct control of a robotic manipulator by a disabled person. The project will develop the basic control strategies and hence the most appropriate input device. The investigation will use the DataGlove™ as the primary input device. The results of this investigation will be used to develop the human interface for the Manus project at the Institute for Rehabilitation Research, Hoensbroek, and for the RTX robot at Tufts University, USA.

Another project focussed on the issues of safety and compliant control of rehabilitative robotic devices. The use of force sensors on a robot arm can detect contact of the arm with the environment. Strategies developed can use this information interactively, and therefore achieve compliant control. The tasks envisaged for such a robotic arm are shaving, feeding and personal hygiene tasks.

The most recent project is to develop a simple robotic alternative to the traditional mouth-stick. This device would be mounted to the wheelchair's lap tray and should be dextrous enough to handle a simple feeding task. It is proposed that the arm should have a maximum of four degrees of freedom and use the patented flexator pneumatic muscle actuator developed by Jim Hennequin.

## 2.4 CONCLUSIONS

The review has shown that there is intensive ongoing activity in rehabilitation robotics. It has also highlighted the different attitudes towards the design of robotic devices for people with disabilities from country to country.

However, even though there has been a vast amount of funds and man-years of effort spent, the ideal of a general purpose rehabilitation robot which can be used by a large number of people with differing disabilities and which is readily available at a low cost is still some way off.

Analysis of the projects showed that even in this narrow field of research there is a diversity of study areas which includes prosthetics, surgery robots, wheelchair-mounted manipulators, mobile fetch and carry robots and workstation systems. One central theme however, within all these projects is that of vocational rehabilitation. Once disabled people are able to work and therefore earn an income, they will become more self sufficient and independent, their self esteem will increase and their social value will be truly realised.

From the review of wheelchair-mounted systems, several important points which might help future projects of this nature have been listed, these are:

- Research in this area requires long-term resources in terms of funds and manpower.
- Research teams have to be multidisciplinary, involving mechanical/electrical engineers, product designers, disabled wheelchair users, psychologists and marketing, sales and support specialists, if they are to have any chance of success.
- Production runs will be in the batch size category, with perhaps 50 to 100 unit sales per year for the most successful systems.
- There is room for both the high and low-tech solutions.
- Investors in projects such as these must believe in cost benefit rather than the fast payback approach. This is why the health authorities and government bodies should initially fund this type of research. There simply is not enough profit to interest large multi-national companies.

There are many reasons why a project fails to reach a production stage. Some of these will be financial, some will be due to a key member leaving, and some will be through a specific design decision made along the way. The following list gives a set of caveats by which the project described in this thesis has attempted to adhere to:

- If the arm has a low functionality, it must have a low cost.
- If the arm has a high functionality, it must have a reasonable cost.

- Researchers should not overlook the needs and abilities of the potential users of their system.
- Limit the scope of the design specification to the fundamental requirements of the system and nothing more.
- The user of an electric wheelchair is disabled enough without having to put up with a large mechanical device attached to the side of their wheelchair, therefore a careful product design approach is required.

To enable the user to perform the desired tasks efficiently and to relieve the user of unnecessary time delay, frustration and fatigue, a reprogrammable microprocessor based control system should be used, even if this exists as an optional extra which can be retro-fitted to the base unit. Many previous systems have failed due to over-specification of the design requirements. Limiting the payload to 1kg and the reach to under 1m should produced the optimum design of a wheelchair-mounted manipulator.

Wheelchair-mounted manipulators will probably follow the socio-economic trends of the market place, with the wealthy and those severely disabled in accidents compensated by large insurance claims buying the high-tech, high-cost product and the poorer buying the low-tech, low-cost product. There will always be a place for both systems. The low-cost solution should, however, penetrate deeper into the market due to its greater accessibility.

Current industrial robot safety regulations prohibit entry of a human into the workspace of a robot, these regulations are inappropriate and unworkable for the application of rehabilitation robotics. There is an urgent need for new regulations, drawn up by researchers in this field to be implemented by regulatory authorities. The legal situation at present is vague. In the event of an accident causing injury or death to the user of an assistive device, the court will consult specialists to ascertain what was the state of best practice in this area at the time of manufacture and to what extent did the designer reach this level of safety in this case.

After a quarter of a century of effort, which has seen the development and growth of the industrial robot industry, the wheelchair-mounted manipulator has just been made available to the general public. Whether this generation of systems will fail to make an impact, as did there predecessors, remains to be seen. It is clear, however, that wheelchair-mounted manipulators have had a number of positive responses from the physically disabled and therefore have a strong role to play in the future of rehabilitation throughout the world.

# Chapter 3

## INVESTIGATION OF USER REQUIREMENTS

---

*'The definition of a scientist: A man who understood nothing,  
until there was nothing left to understand.'*

*The Omega Man, 1976.*

---

### 3.1 INTRODUCTION

In the area of rehabilitation robotics many otherwise good designs have failed to be bought and used by disabled people due to some basic design flaws, eg too expensive, not ergonomically suitable, too difficult to control, and probably the most important flaw was the fact that disabled people were excluded from the initial stages of the design process. The results of the survey reported here (Prior, 1990b) will be used to develop the design specification for a wheelchair-mounted manipulator which does not fall into these traps.

To the author's knowledge only one other similar survey of the severely disabled has been conducted in the UK using a questionnaire. This was conducted by Bath Institute of Medical Engineering (B.I.M.E.) together with The Royal National Hospital for Rheumatic Diseases, in 1986 (Clay et al, 1987). The results of the Bath survey showed the need for a robotic device to aid the severely disabled; 60% of the subjects considered that the system would be of use to them, and 43% would consider buying it. Other surveys have been conducted, but these have been mainly confined to the USA (Faletti & Clark, 1984; Glass & Hall, 1987; Leifer, 1981).

The reasons for conducting another survey were as follows:

1. To verify, update and expand upon the findings of the Bath survey;
2. Because no robotic aid survey of electric wheelchair users had ever been conducted;
3. To involve disabled people at the earliest opportunity in the design process;
4. To involve Occupational Therapy units and colleges in this new area of technology;
5. To provide a better understanding of the problems of being disabled.

### **3.2 THE BATH SURVEY CONCLUSIONS**

The Bath survey established the need for a robotic aid system amongst severely disabled people who are alone for significant periods of time.

As a possible accessory to the next generation of environmental control units the B.I.M.E. robotic device could be prescribed to an estimated 80-90% of the survey subjects. It was concluded from the survey that a mobile device would be of far greater use than a workstation-based device. The B.I.M.E. research team have developed and tested a movable robotic workstation, based on a purpose-built robotic arm capable of tasks such as feeding, retrieving books from a shelf and operating a cassette recorder/radio. This unit was tested at the Odstock spinal injuries unit in Salisbury.

Future plans include a wheelchair-mounted version of the above system to enable it to perform in an unstructured environment.

### **3.3 THE MIDDLESEX ROBOTIC AID QUESTIONNAIRE**

The Robotic Aid Questionnaire (see Appendix A) was designed and developed with the help of the director of orthotics, occupational therapists and patients from the Royal National Orthopaedic Hospital, Stanmore, Middlesex. The questionnaire was loosely based on the Bath questionnaire with some major changes regarding the sections involving daily living tasks. The Bath questionnaire at 11 pages was considered too long, and therefore a maximum of 5 pages was set for the document. The questionnaire was modified a number of times to suit all parties concerned, the final version being four pages long and containing over 110 questions. The first page asked general questions on the subjects' circumstances, ie age, sex, employment, etc these were based closely on the Bath questions to aid comparison. The second and third pages contained detailed questions on the subjects' daily living tasks, these were grouped into four separate sections, based on the work carried out at the V.A. Medical Center (Leifer, 1981), Palo Alto, USA.

These sections are:

1. Personal hygiene tasks;
2. Domestic tasks;
3. Leisure & recreation tasks, and
4. Working environment tasks.

The last page contained questions on the disabled persons top five tasks (tasks the user would most like to do, but could not), input device familiarity and contact address.

### 3.3.1 Method of Survey

Initially it was felt that due to the high number of questions, the survey could not successfully be conducted by post. Mr J.I.L. Bayley (Director of the London Spinal Unit) suggested that an approach be made to some occupational therapist training colleges to enquire whether they would be willing to take on the questionnaire survey as a project for their final year students. All the occupational therapist training colleges in the UK were written to and three accepted the task :

- The London School of Occupational Therapy;
- Glasgow School of Occupational Therapy, and
- Queen Margaret College, Edinburgh.

The total number of questionnaires sent out by these three colleges was approximately 150; however, only eight completed questionnaires were returned. This prompted the author to change his approach, and through various sources (see Appendix A), a total of 50 questionnaires were eventually completed by the end of June 1989. The highest number of responses was through the Disablement Services Authority (DSA), the government body which was responsible for distributing electric wheelchairs to disabled people. A list of 30 electric wheelchair users in the Brent and Wembley areas was obtained from the DSA. Each disabled person was then written to, 15 with the questionnaire, and 15 without it asking for a convenient time to visit. The response rate eventually rose to 50% after some follow-up using the telephone. The questionnaire was accompanied by a video showing a computer simulation of the conceptual design performing a number of everyday tasks (Prior, 1991b; Prior, 1993b).

### 3.3.2 Subject Criteria

The criteria by which the subjects for the survey were selected were as follows:

- They must be severely physically disabled with little or no upper body ability, and
- They should also be using an electric wheelchair, though this was not essential.

### 3.3.3 Results

The data collected from the questionnaires was processed by a computer program which grouped and updated the information into convenient blocks. At the end of the survey the data file was loaded into a Lotus spreadsheet program on an IBM compatible PC, and the results presented graphically in the order in which the questions appear on the questionnaire.

### 3.3.3.1 Age distribution (see figure 3.1)

Figure 3.1 shows that the age distribution forms a positively skewed normal curve. This compares with a negatively skewed normal curve from the Bath survey. This could be due to the smaller Bath survey size of 42 subjects, the lower number of age groups in the Bath survey (five groups between 16 and 65 years), or the influence of the lower average age of the spinal cord injured group (24% of the total subjects) in this survey. The average age of the survey subjects was 40 years old, they should therefore be reasonably familiar (comfortable) with using new technology, ie electronic machines, computers.

### 3.3.3.2 Sex distribution

The survey contained 56% male and 44% female subjects, this can be compared with 64% male and 36% female subjects from the Bath survey. It would therefore seem that there are more male electric wheelchair users than female, this may be due to the high number of spinal injuries caused by male participation in dangerous sports such as diving, skiing, martial arts, together with motor cycle injuries, etc. The national figures from the O.P.C.S. survey of disability (Martin et al, 1988) for the highest severity categories are: 35% male and 65% female, however these include large numbers of women aged over 75. This is due to the fact that women tend to live longer than men and hence suffer from conditions related to old age, ie arthritis, senile dementia, etc.

### 3.3.3.3 Marital status (see figures 3.2 & 3.3)

Figure 3.2 shows the marital status of the survey subjects, it can be seen that there are almost three times as many single subjects as married ones. Unfortunately there is no information in this survey on how many disabled people were married before onset of their disability. Figure 3.3 shows the relationship between the marital status of the survey subjects with their type of abode, here it can be seen that there are more than twice as many single people than married people living at home, and that there are six times as many single people than married people living in a communal establishment. A robotic aid might allow some of those people living in communal establishments to be more self-sufficient and hence be able to live in their own homes.

### 3.3.3.4 Type of abode (see figure 3.4)

Figure 3.4 shows the type of abode of the survey subjects. The vast majority of the survey subjects were living at home. These findings reiterate the Bath findings and hence the robotic aid must be designed to operate within the confines of the home environment.



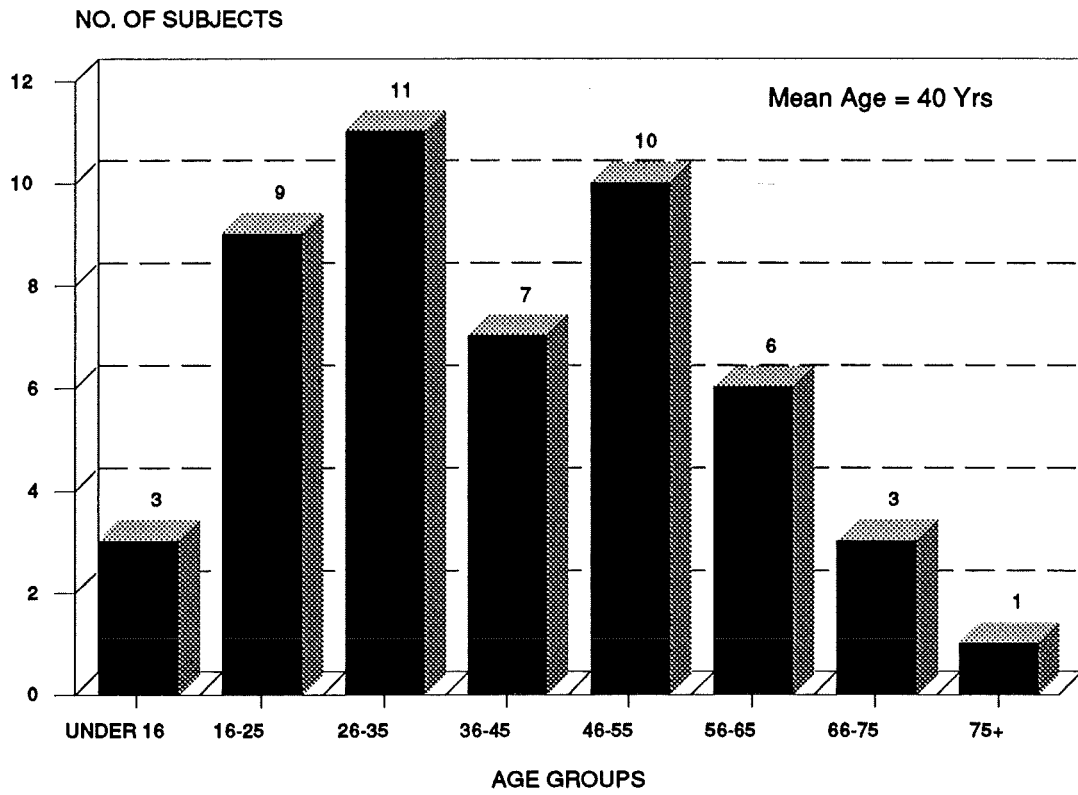


Figure 3.1 - Age distribution of survey subjects.

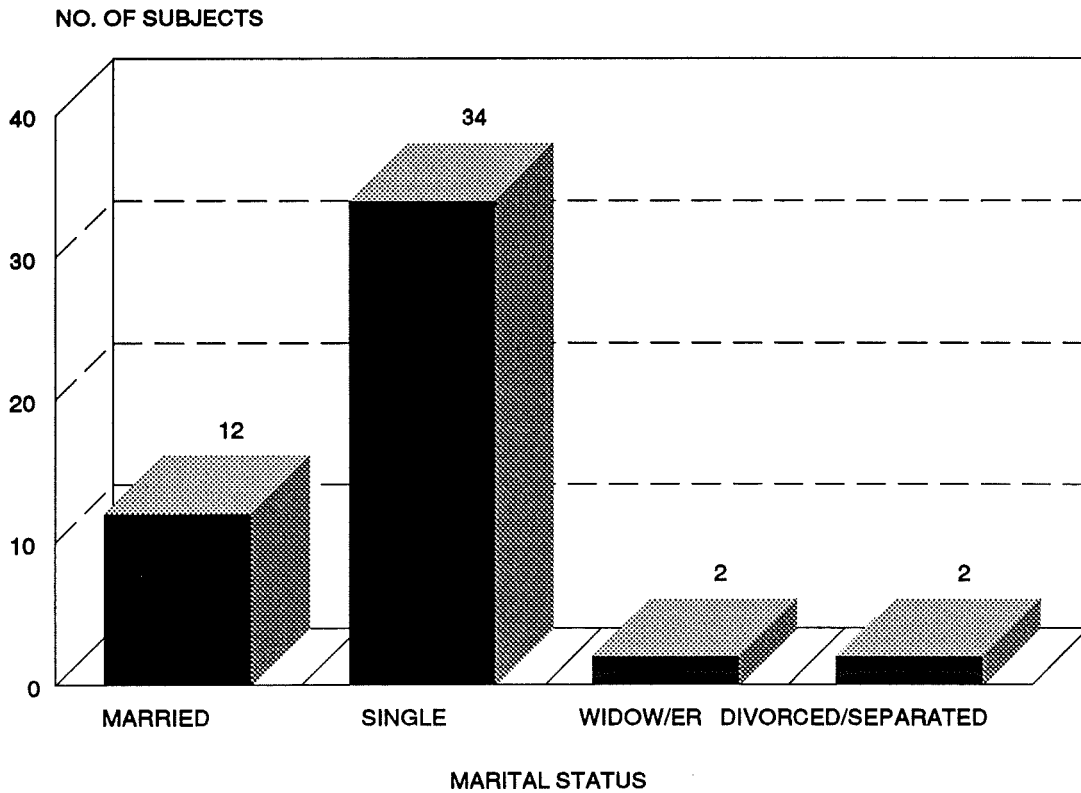


Figure 3.2 - Marital status of survey subjects.

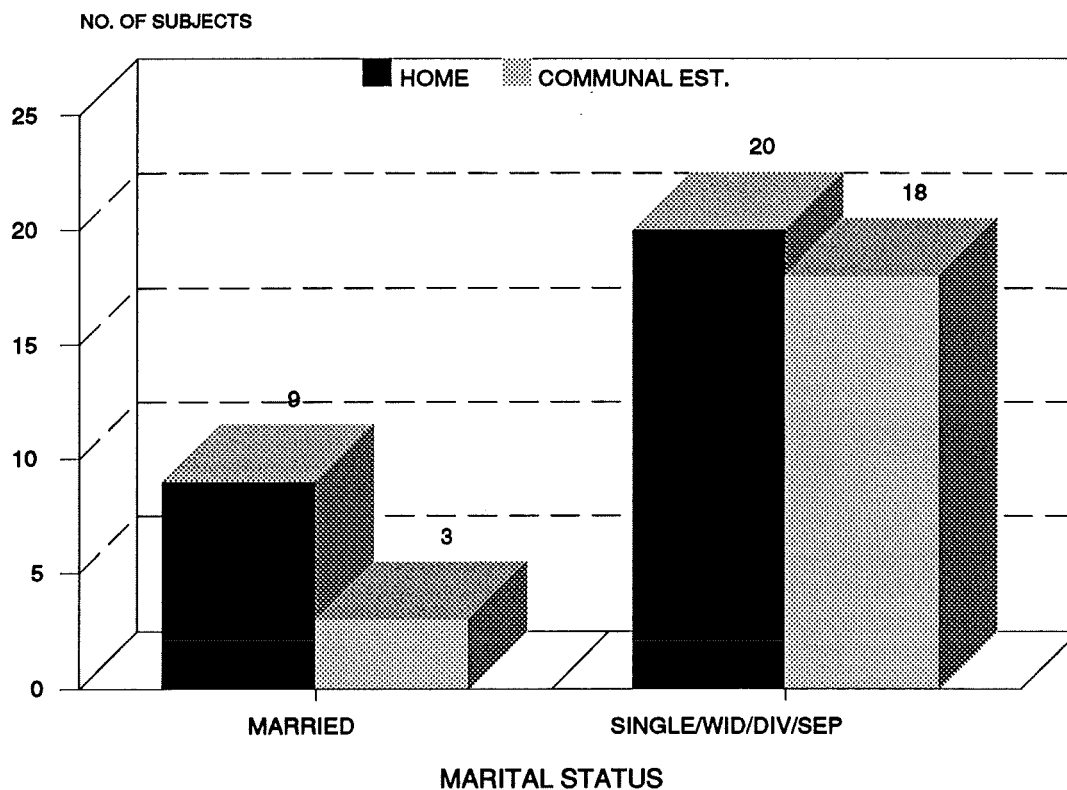


Figure 3.3 - Marital status and type of abode.

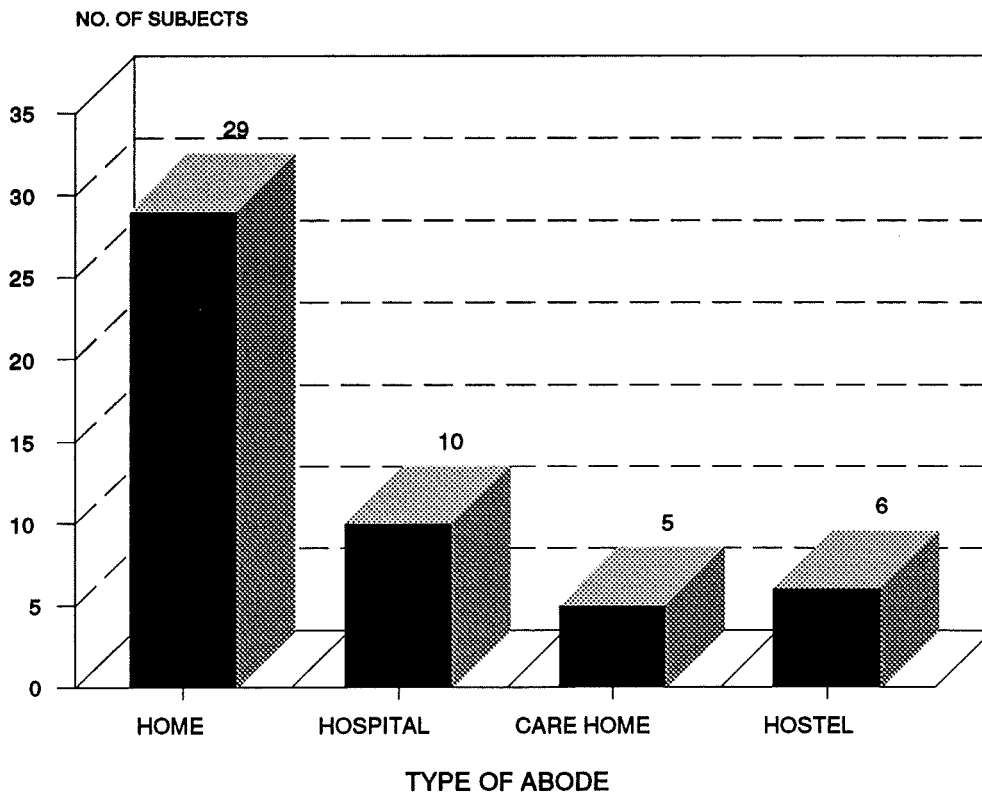


Figure 3.4 - Type of abode of survey subjects.

### 3.3.3.5 Analysis of subjects living at home (see figures 3.5 & 3.6)

Of the subjects at home, by far the greatest majority were living with family or a partner, only three out of twenty-nine were living alone. Of the subjects living at home the majority receive no care assistance. This shows the heavy burden placed on the families of disabled people if they are to be able to live at home. A robotic aid would be able to relieve some of the burden placed on the family and allow the disabled person to regain some of their independence and self esteem. The OPCS survey estimated that there are almost one million unpaid carers in the UK alone.

### 3.3.3.6 Employment of survey subjects (see figure 3.7)

Out of the 43 survey subjects of working age, 79% were unemployed. This compares with 93% of the Bath survey, and is an indictment of our society. Robotic aids have been used in the working environment in the USA and have proved to be very useful, provided the type of work is carefully selected. Current research in this area is underway at Cambridge University in collaboration with the Papworth Group (Dallaway & Jackson, 1992).

### 3.3.3.7 Pastimes (see figure 3.8)

In common with the Bath survey the most popular pastime was watching television (3.82 hr/day), running a close second was listening to the radio (3.32 hr/day). Of the other pastimes, reading and listening to the hi-fi were fairly popular, however, not much interest was found in stamp collecting or using a C.B. radio.

### 3.3.3.8 Spinal cord injuries (see figures 3.9 & 3.10)

Of the survey sample the most prevalent disability was spinal cord injury (SCI), this may to some extent be due to the close links with the spinal injuries units and the Association for Spinal Injury Research Rehabilitation and Reintegration, (A.S.P.I.R.E.). The highest frequency of spinal injury occurred at C5 and C6 (four subjects each), due to the subject criteria spinal cord injuries lower than C7 were not selected (see figure 3.9). People with lesions at C7 and lower are usually able to operate non-powered wheelchairs and hence were excluded from the survey. Of the 12 SCI subjects, twice as many were complete as were incomplete (see figure 3.10).

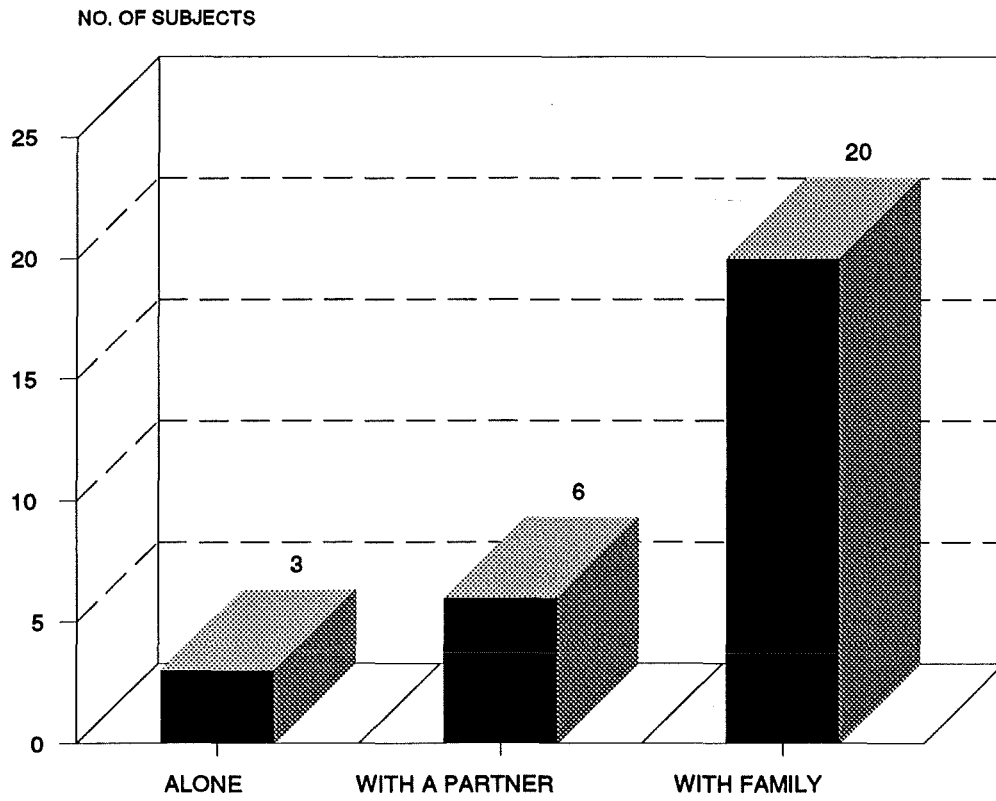


Figure 3.5 - Analysis of subjects living at home.

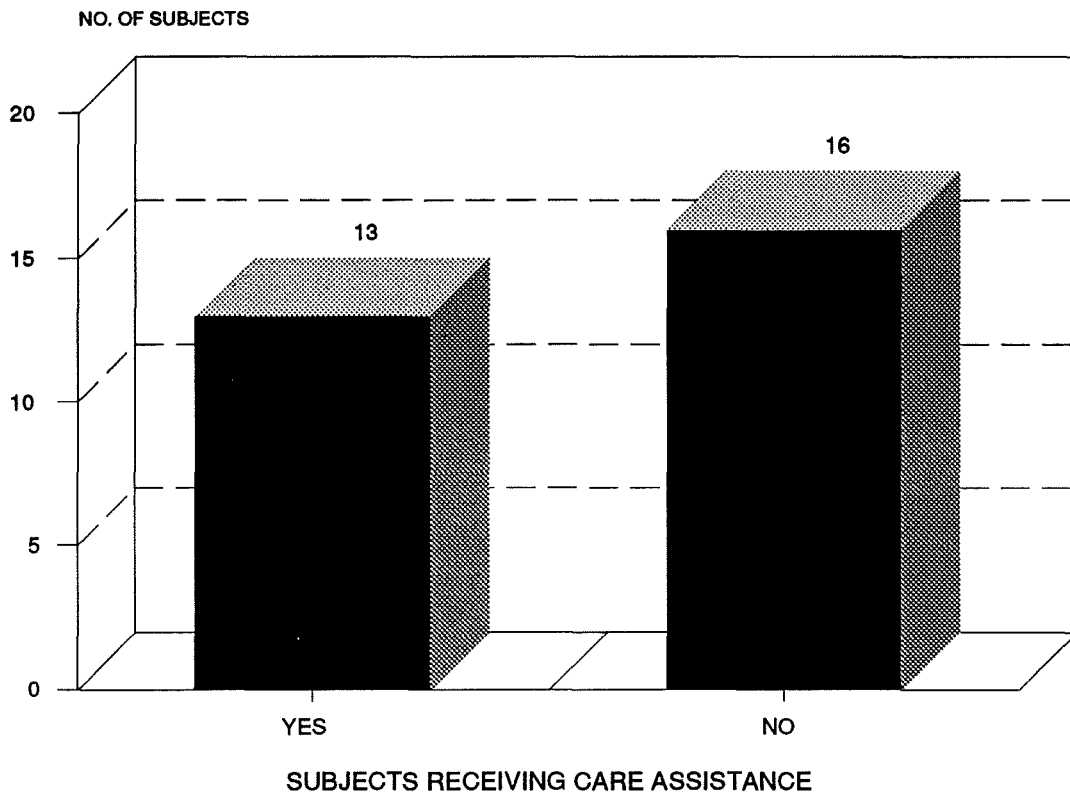


Figure 3.6 - Care assistance of subjects living at home.

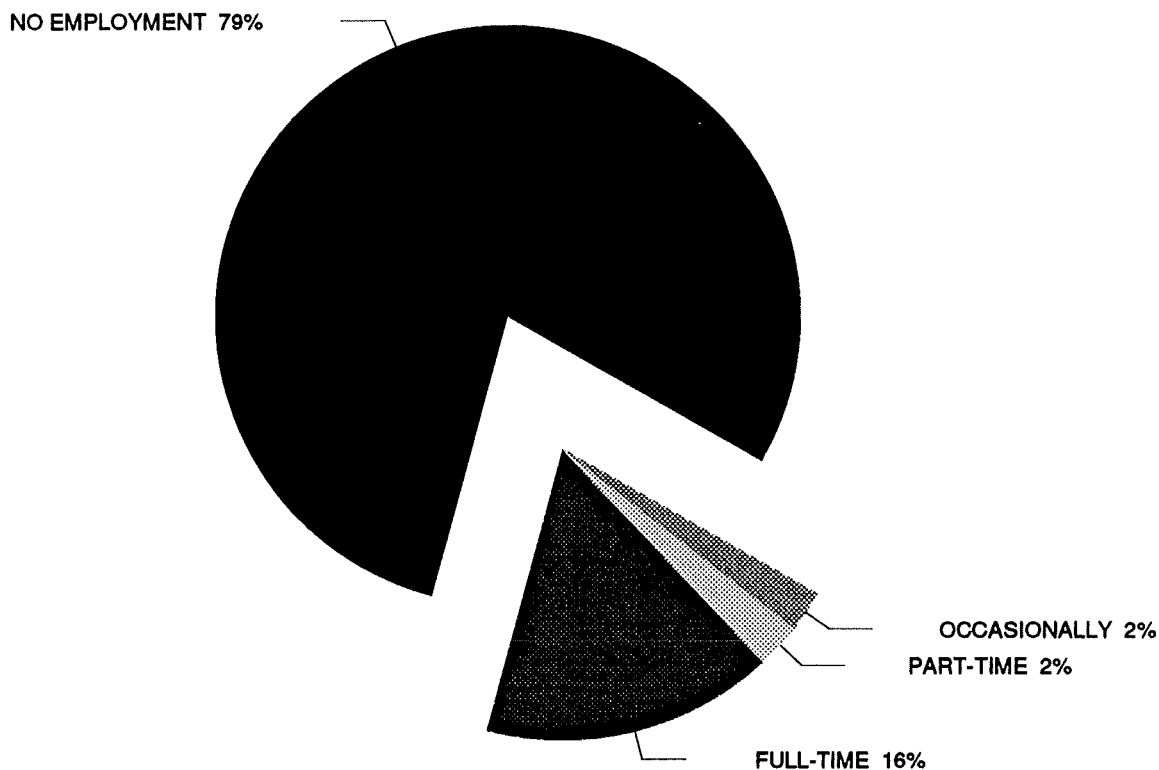


Figure 3.7 - Employment status of survey subjects aged 16-65

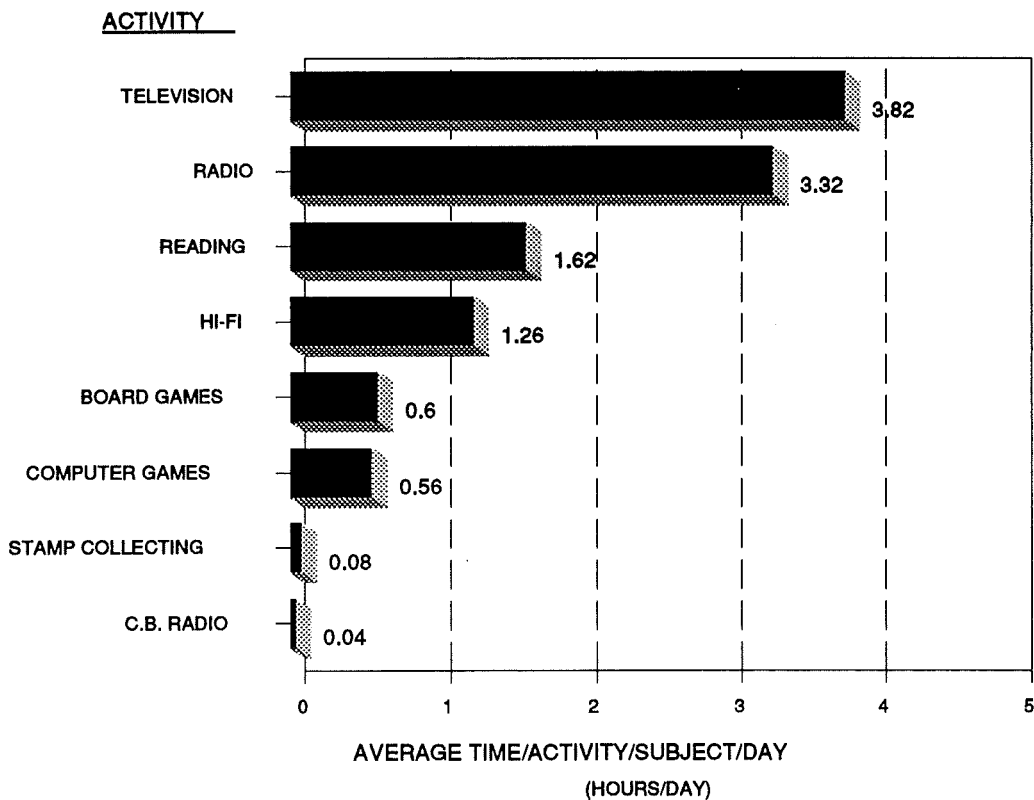


Figure 3.8 - Most popular pastimes (survey size = 50).

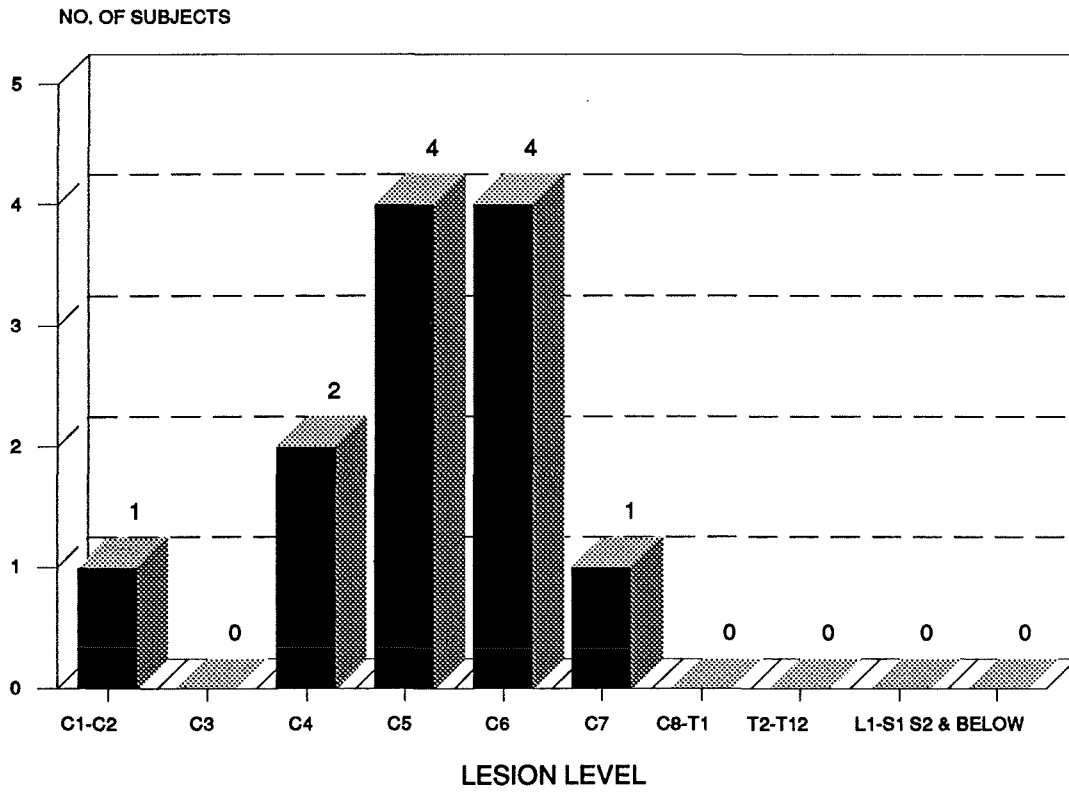


Figure 3.9 - Spinal cord injuries: lesion level frequency.

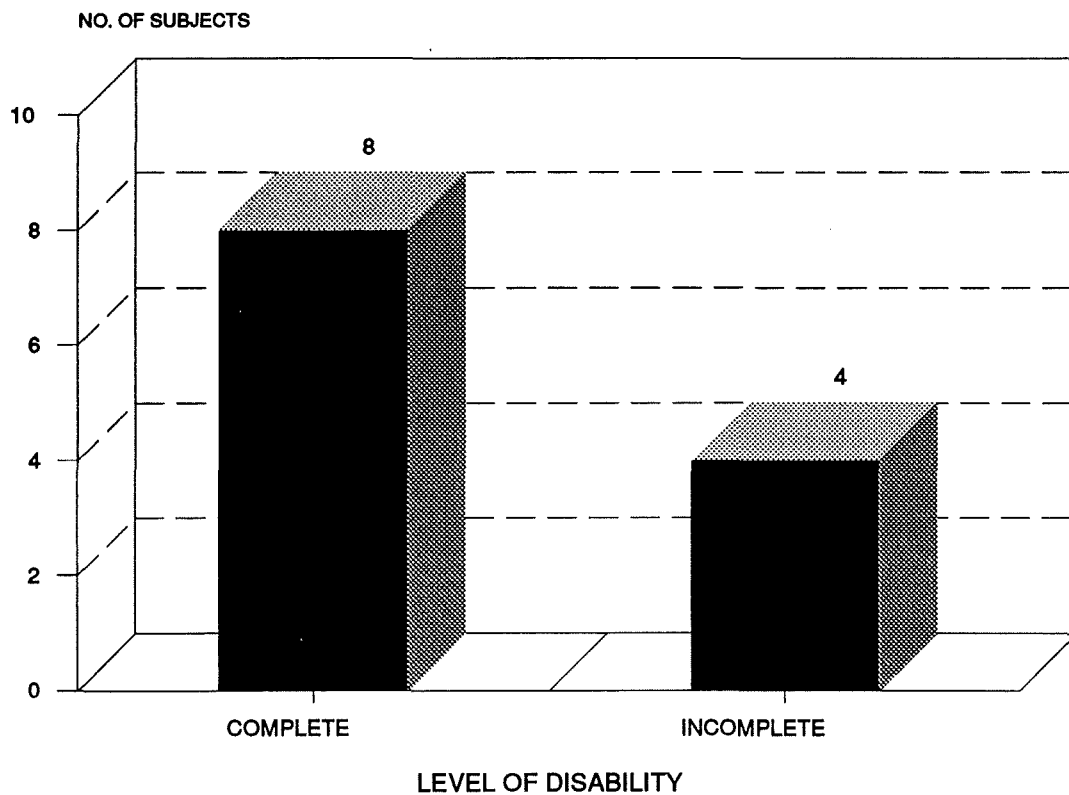


Figure 3.10 - Spinal cord injuries: level of disability.

### *3.3.3.9 Percentage of survey subjects suffering from involuntary movements in parts of their body (see figure 3.11)*

Figure 3.11 shows how the survey subjects were affected in the different parts of their body by involuntary movements. Involuntary movements of the hands, arms and legs tend to remain constant at approximately 20-26%. This is within the bounds of the Bath survey of between 14-36%. This large % band is probably due to the greater incidence of Multiple Sclerosis (M.S.) in the Bath survey. This information is vital when considering the most appropriate type of input device to control the manipulator.

### *3.3.3.10 Type of disability (see figure 3.12)*

As previously stated the greatest prevalence of any type of disability was for spinal cord injury (24%), this was followed by multiple sclerosis (16%), rheumatoid arthritis & cerebral palsy (10%). This agrees with published figures that approximately 50% of those severely disabled will be classified as very severely disabled (ie SCI, MS) (Dymond et al, 1988). This compares with the Bath results of MS (60%) and SCI (24%), these being the most prevalent disabilities.

### *3.3.3.11 Personal hygiene tasks*

The personal hygiene tasks found impossible were, washing hair (78%), re-dressing after going to the toilet (56%) and cleaning after going to the toilet (48%). Clearly these tasks are of a nature that even a 'state of the art' robot would find either very difficult or impossible to assist with at present.

### *3.3.3.12 Domestic tasks*

Domestic tasks found impossible to do were, filling a kettle (68%), cooking (64%), opening/closing windows (62%), preparing food (58%) and preparing utensils (54%). These compare with cooking (64%) and preparing food (62%) from the Bath survey results. Some of these tasks would be appropriate for a robotic aid, and will form part of the design specification.

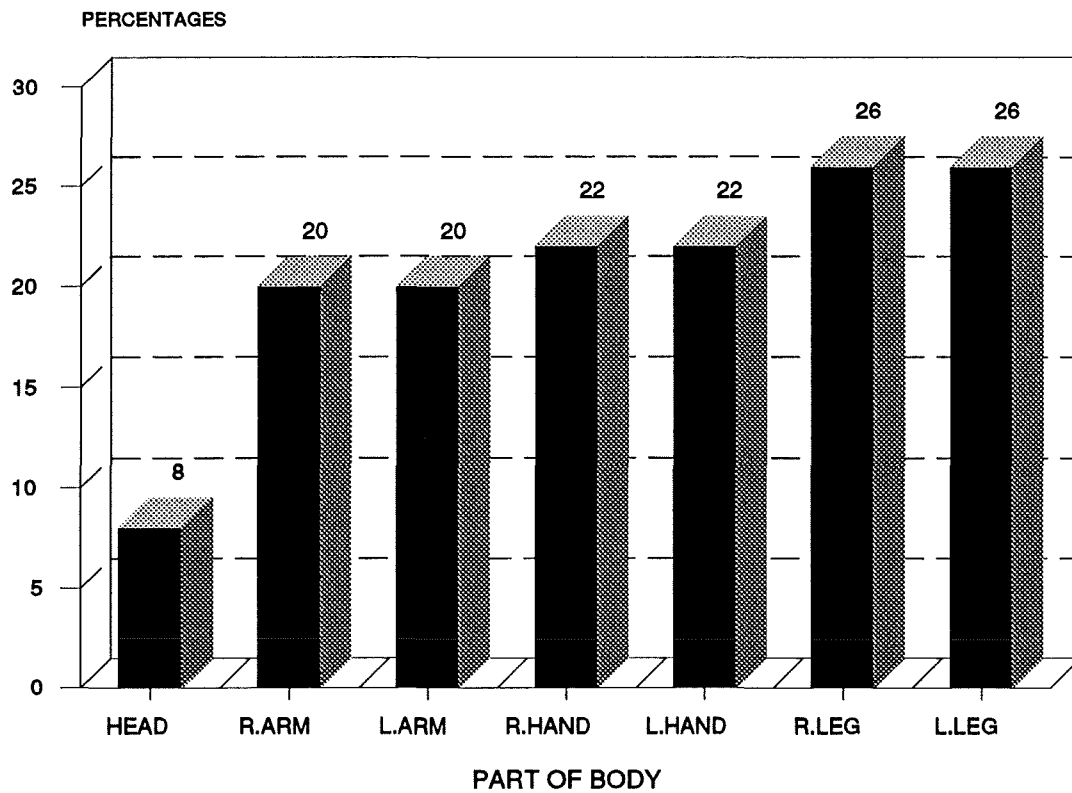


Figure 3.11 - Involuntary movements of survey subjects.

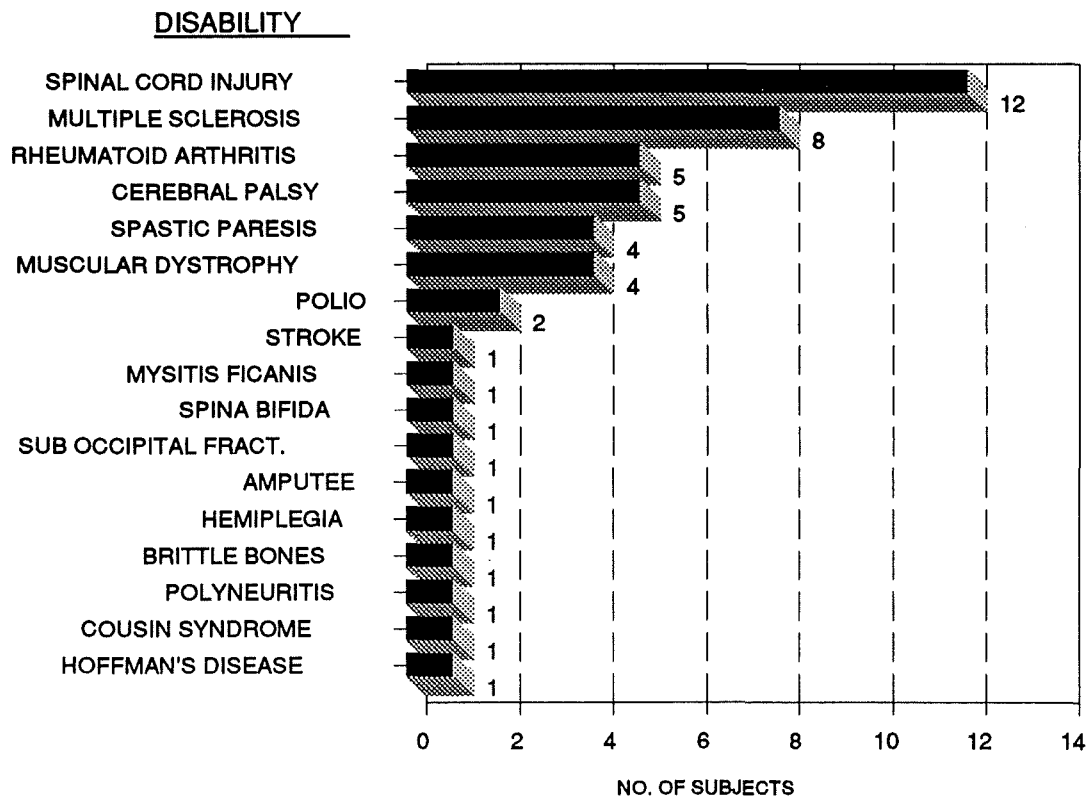


Figure 3.12 - Type of disability (survey size=50).



### 3.3.3.13 Leisure & recreational tasks

Tasks found impossible were, gardening (48%), opening wine bottles (48%) and sports activities such as shooting (44%), bowls (40%), fishing (38%); however, these also have high non-applicable percentage values. These results indicate the difficulty that disabled people find in pursuing leisure and sporting activities, again some of these tasks will form part of the design specification.

### 3.3.3.14 Working environment tasks

Tasks found impossible include, posting a letter (30%), filing documents (28%) and opening a letter (26%). Many of these tasks have high non-applicable percentage values, this is probably due to the high proportion of unemployed subjects (78%). This is an area where a great difference can be made in the lives of disabled people by the use of a robotic aid.

### 3.3.3.15 Top five tasks (see figure 3.13)

This section gave the subjects the opportunity to say which five tasks they would most like to be able to do but cannot, due to their disability. The results show that the most popular choice was reaching, stretching and gripping (22), the second choice was somewhat of a surprise, gardening (13), followed by reaching to the floor (12), cooking (10) and eating/feeding (9). These tasks together with some of those mentioned in the other sections, will form the main list of tasks which the robotic arm will be designed to perform.

### 3.3.3.16 Possible consumer population (see figure 3.14)

When asked the question: Would the subject consider buying such a device if it could perform some of his/her top five tasks? 84% said they would consider buying it, provided it was within their means to do so. This compares with 43% from the Bath survey for a target price of £2000. Perhaps this shows the growing acceptance of high-tech aids for the disabled.

### 3.3.3.17 Input device familiarity

84% of the survey subjects were familiar with and had used a joystick, 72% were familiar with and had used a remote control unit. Of the more sophisticated forms of input devices, e.g. ultrasonic and eye movement, very few had used them and many were still unfamiliar with them. This would indicate that the conventional joystick is still

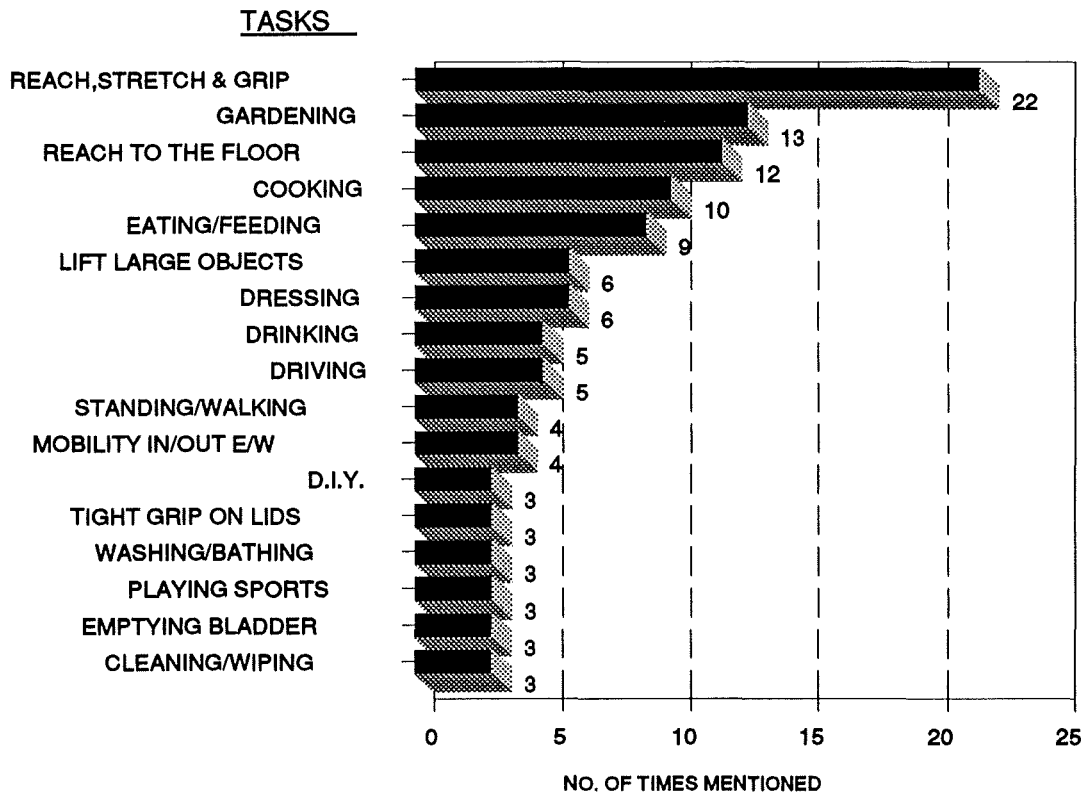


Figure 3.13 - Possible task list of a robotic aid.

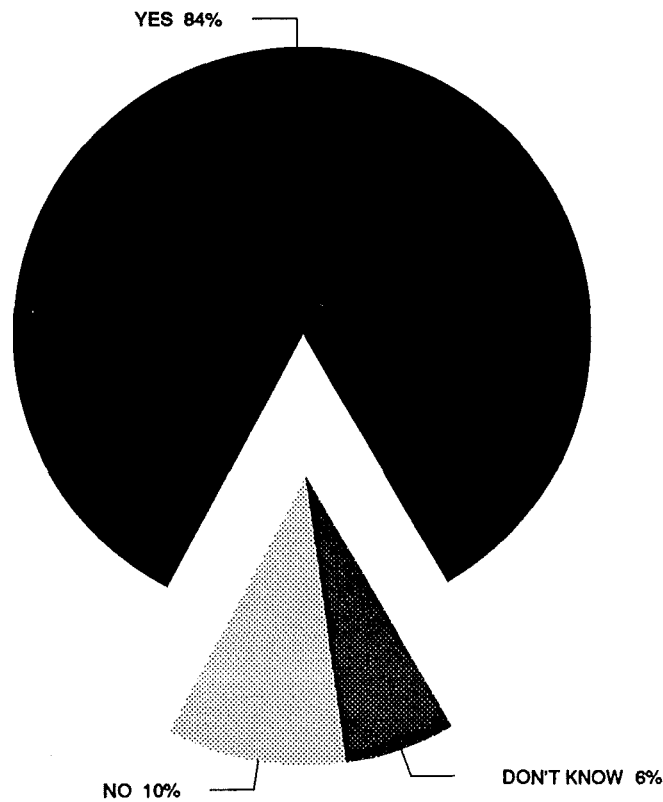


Figure 3.14 - Subjects likely to purchase a robotic aid.

the most familiar input device.

Due to the large number of disabling conditions and subsequent physical effects, the selection of the most appropriate input device is a very difficult one, and will undoubtedly contribute to the success or failure of the design. The availability and decreasing cost of voice recognition systems make them a potential strong contender in this area; however, conventional two and three degree of freedom joysticks, due to their low cost and reliability are also likely choices.

### *3.3.3.18 Practical trial stage*

There was a good response to the question about whether the subjects would be willing to take part in a practical trial, with 84% stating that they would. When a prototype model is ready to be evaluated, selected subjects will be asked to test the equipment in their own homes and to give their comments and criticisms. These will then be used in the modification/redesign phase of the project.

## **3.4 THE QUEEN MARGARET COLLEGE SURVEY**

The Queen Margaret occupational therapist training college, Edinburgh decided to conduct their own survey of electric wheelchair users, using a slightly modified version of the original questionnaire. The results of this independent survey are reported here as additional findings, which support the conclusions of the main research survey.

The survey was conducted with the help of nine final year students while on clinical placement at various hospitals in Scotland. The survey size was too small to be representative of the wheelchair-bound population (only eight returned questionnaires). However, a summary of their findings is given below.

### **3.4.1 Summary of the Survey Results**

- Average age: 43 yrs;
- Age range: 27-68 yrs;
- Male: 50% Female: 50%;
- People living alone 0%; People receiving help if needed 88%;
- Unemployed: 50%; Retired: 25%; Housewife: 12.5%; Further education: 12.5%;
- Approximately 70% could not hold a cup, a further 12.5% had difficulty, and
- 75% used a hand operated joystick; 25% used a chin operated joystick.

### 3.4.2 Most Important Task Lists

#### Personal Hygiene Tasks (% Experiencing Great Difficulty)

88% Rearranging Clothes  
63% Blowing Nose  
63% Cleaning After Toilet  
50% Washing Face/Hands  
50% Shaving/Makeup

#### Leisure and Recreational Tasks (% Experiencing Great Difficulty)

50% Playing Snooker  
50% Operating the Radio  
38% Operating a Record Player  
38% Reading a Newspaper  
38% Scribbling

#### Domestic Tasks (% Experiencing Great Difficulty)

75% Using a Knife  
63% Filling the Kettle  
63% Pouring Water/Milk  
63% Opening/Closing Windows  
63% Operating Switches

#### Working Environment Tasks (% Experiencing Great Difficulty)

75% Opening a Letter  
63% Placing a Letter in an Envelope  
63% Sealing an Envelope  
50% Inserting a Floppy Disk  
50% Answering the Telephone

- 63% said that they would consider buying a robotic arm; 37% said that they were unsure; 0% said no.
- 88% said that they would be willing to take part in a clinical trial.
- The top tasks mentioned were: 'picking things up from the floor' and 'operating a radio/cassette/video.'

These results match closely those found from the main survey. This further verifies and validates the main results.

## 3.5 QUESTIONNAIRE RESULTS AND THE DESIGN SPECIFICATION

The preliminary design specification, written before the questionnaire survey was complete, contained very little information directly related to the final questionnaire results. It was therefore necessary to establish a link between the '*Most Important Tasks*', as defined by the questionnaire subjects, ie those tasks that they found difficult or impossible to do, and the '*Most Feasible Tasks*', those tasks that the robotic arm could reasonably be expected to undertake. This link was achieved by using the weighted matrix method, based on the criteria of cost, control complexity, accuracy and payload. The tasks with the highest scores are the most feasible tasks for the robot arm to be designed to undertake. The high scoring tasks have also been analysed to estimate the minimum number of degrees of freedom required of a robotic arm, to undertake

these tasks.

The results should aid in the formulation of the final design specification which is detailed in the next chapter of the thesis.

### 3.5.1 Summary of the Questionnaire Results

The average electric wheelchair user was 40 years old, single, living at home with family support and was not receiving any care assistance. The most prevalent disabilities were Spinal Cord Injury (24%) and Multiple Sclerosis (16%). The most popular pastimes were watching television (3.82 hr/day) and listening to the radio (3.32 hr/day). 79% of the survey subjects who were of working age were unemployed. 50% of the survey subjects described their disability as partial and 20-26% suffer from involuntary movements in their limbs.

The survey results clearly show the need for an aid to daily living, not only to provide the user with a greater degree of independence but also to give them a better quality of life. One of the most important areas of need is in the vocational field, to enable the user to regain their self esteem and show their true worth.

### 3.5.2 Most Important Task Lists (see Appendix A)

#### Personal Hygiene Tasks

(% with Difficulty + %Not at all)

88% Washing Hair  
80% Rearranging Clothes After Toilet  
68% Cleaning After Toilet  
54% Combing Hair  
54% Shaving/Makeup

#### Domestic Tasks

(% with Difficulty + %Not at all)

84% Cooking  
82% Preparing Food  
78% Filling the Kettle  
78% Opening/Closing Windows  
70% Pouring Water/Milk

#### Leisure and Recreational Tasks

(% with Difficulty + %Not at all)

58% Pick-up and Throw Objects  
54% Opening a Wine Bottle  
52% Gardening  
46% Shooting  
44% Playing Snooker/Pool

#### Working Environment Tasks

(% with Difficulty + %Not at all)

48% Opening a Letter  
48% Using a Stapler  
46% Posting a Letter  
44% Pick and Place Objects  
44% Filing Documents

Observation of the percentage values of the *Working Environment* and *Leisure & Recreational* tasks shows that these are much lower than the other sections. This can be directly attributable to the fact that at the present time the majority of disabled people are unemployed and take little part in sports and recreational activities.

### 3.5.3 The Weighted Matrix Method (Middendorf, 1986)

In this method, a weighted decision matrix using quantitative and qualitative criteria is used to obtain numerical values for a given set of independent variables. We assign to each of the criteria a weight based upon their value compared to each other. These values may be entirely arbitrary, but are usually based on previous experience and common sense. The weights of the criteria should be such that their sum adds up to one, as this aids checking and simplifies arithmetic.

Each of the tasks in this example is judged against each of the criteria, and depending upon how well each task satisfies each criteria, a score is awarded. The sum of the individual scores is multiplied by the criterion weighting to give an overall score for the particular task. The task with the highest score is in theory the easiest of the selected tasks to be incorporated into the design of the robotic arm. The overall scores can vary from 0 to 1, and because there were five variables in each section the mean value would be 0.2. Tasks with scores below 0.2 should be looked at carefully before being accepted as potential design tasks.

The results using the weighted matrix method helps to establish a priority task list upon which the designer can draft the design specification, with the knowledge that these tasks are directly related to the user's needs. Too often in rehabilitation robotics the design specification has been derived from the designer's perspective of what the users' needs are.

#### 3.5.3.1 *Weighted matrix results*

Table 3.1 on the following page contains the results of the weighted matrix method as applied to the tasks listed in the questionnaire survey. The choice of the criteria used and their relative weighting is purely subjective, based on the designers knowledge of the particular application and its most important constraints. Though crude, this method does give a more analytical approach to determining which are the most feasible tasks for which the arm should be designed to undertake.

Table 3.1 - Weighted Matrix Results

| WEIGHTED MATRIX CRITERIA                |         |            |          |         |                    |
|---|---------|------------|----------|---------|--------------------|
|   | (0.4)   | (0.3)      | (0.2)    | (0.1)   |                    |
|   | Control |            |          |         |                    |
|   | Cost    | Complexity | Accuracy | Payload | Score              |
| <b>Personal Hygiene Tasks</b>           |         |            |          |         |                    |
| Washing Hair                            | 0.1     | 0.1        | 0.2      | 0.15    | 0.125              |
| Re-arranging Clothes                    | 0.25    | 0.2        | 0.2      | 0.2     | 0.220              |
| Cleaning after the Toilet               | 0.1     | 0.15       | 0.15     | 0.2     | 0.135              |
| Combing Hair                            | 0.3     | 0.3        | 0.2      | 0.2     | 0.270              |
| Shaving/Makeup                          | 0.25    | 0.25       | 0.25     | 0.25    | 0.250              |
| <b>Domestic Tasks</b>                   |         |            |          |         |                    |
| Cooking                                 | 0.2     | 0.2        | 0.2      | 0.15    | 0.195              |
| Preparing Food                          | 0.1     | 0.1        | 0.1      | 0.25    | 0.115              |
| Filling the Kettle                      | 0.2     | 0.2        | 0.2      | 0.15    | 0.195              |
| Opening/Closing Windows                 | 0.2     | 0.2        | 0.25     | 0.2     | 0.210              |
| Pouring Liquid                          | 0.3     | 0.3        | 0.25     | 0.25    | 0.285 <sup>1</sup> |
| <b>Leisure &amp; Recreational Tasks</b> |         |            |          |         |                    |
| Pick-up & Throw Objects                 | 0.1     | 0.2        | 0.3      | 0.15    | 0.175              |
| Gardening                               | 0.3     | 0.2        | 0.25     | 0.2     | 0.250              |
| Opening a Wine Bottle                   | 0.2     | 0.2        | 0.15     | 0.2     | 0.190              |
| Playing Pool/Snooker                    | 0.2     | 0.25       | 0.15     | 0.25    | 0.210              |
| Shooting                                | 0.2     | 0.15       | 0.15     | 0.2     | 0.175              |
| <b>Working Environment Tasks</b>        |         |            |          |         |                    |
| Opening a Letter                        | 0.15    | 0.15       | 0.15     | 0.2     | 0.155              |
| Using a Stapler                         | 0.15    | 0.2        | 0.2      | 0.15    | 0.175              |
| Posting a Letter                        | 0.3     | 0.25       | 0.25     | 0.15    | 0.270              |
| Pick & Place Objects                    | 0.2     | 0.2        | 0.2      | 0.2     | 0.200              |
| Filing Documents                        | 0.2     | 0.2        | 0.2      | 0.2     | 0.200              |
| <b>Other Tasks</b>                      |         |            |          |         |                    |
| Drinking                                | 0.3     | 0.3        | 0.25     | 0.15    | 0.275              |
| Painting                                | 0.3     | 0.3        | 0.25     | 0.25    | 0.285 <sup>1</sup> |
| Writing/Typing                          | 0.15    | 0.15       | 0.15     | 0.2     | 0.155              |
| Showering                               | 0.1     | 0.1        | 0.2      | 0.15    | 0.125              |
| Creaming                                | 0.15    | 0.15       | 0.15     | 0.25    | 0.160              |
| <b>Top Five Tasks</b>                   |         |            |          |         |                    |
| Reaching, Stretching & Gripping         | 0.2     | 0.25       | 0.25     | 0.2     | 0.225              |
| Pick & Place from Floor                 | 0.2     | 0.25       | 0.2      | 0.2     | 0.215              |
| Eating/Feeding                          | 0.3     | 0.2        | 0.15     | 0.3     | 0.240              |
| Dressing                                | 0.15    | 0.1        | 0.2      | 0.2     | 0.150              |
| Pick-up Large or Heavy Objects          | 0.15    | 0.2        | 0.2      | 0.1     | 0.170              |

Table 3.2 - Highest Scoring Tasks (weighted matrix results)

| Task                       | Questionnaire Section | Overall Score | D.O.F. Estimated Min. |
|----------------------------|-----------------------|---------------|-----------------------|
| Pouring liquid             | Domestic              | 0.285         | 4                     |
| Painting                   | Other tasks           | 0.285         | 5                     |
| Drinking                   | Other tasks           | 0.275         | 4                     |
| Posting a letter           | Working environment   | 0.270         | 4                     |
| Combing hair               | Personal hygiene      | 0.270         | 5                     |
| Gardening                  | Leisure & recreation  | 0.250         | 5                     |
| Shaving/makeup             | Personal hygiene      | 0.250         | 5                     |
| Eating/feeding             | Top five tasks        | 0.240         | 5                     |
| Reaching, stretch. & grip. | Top five tasks        | 0.225         | 6                     |
| Re-arranging clothes       | Personal hygiene      | 0.220         | 6                     |
| Pick & place from floor    | Top five tasks        | 0.215         | 5                     |
| Open/close windows         | Domestic              | 0.210         | 5                     |
| Playing pool/snooker       | Leisure & recreation  | 0.210         | 4                     |
| Pick & place objects       | Working environment   | 0.200         | 5                     |
| Filing documents           | Working environment   | 0.200         | 5                     |
| Cooking                    | Domestic              | 0.195         | 5                     |
| Filling the kettle         | Domestic              | 0.195         | 5                     |
| Pick-up & throw objects    | Leisure & recreation  | 0.175         | 6                     |

The table above shows the most appropriate tasks for the manipulator and will be used in the design specification stage to define those tasks which the wheelchair-mounted manipulator will be designed and programmed to perform. These tasks have important implications in the design of the arm, ie payload, speed of operation, type of end effector, etc.

### 3.6 CLINICAL EVALUATION OF THE MASTER SYSTEM

The French MASTER project began in the late 1980's by the robotics department of the French Atomic Energy Commission. The latest system consists of a modified UMI R100 robot arm built into a workstation environment. MASTER can be used in both direct and automatic modes. From the beginning of 1991, three prototypes were clinically evaluated in French rehabilitation centres for a period of one year (Cammoun et al,



1992). This makes the results of this evaluation particularly relevant, due to the long evaluation period and up to date findings. This section will give a synopsis of the clinical evaluation results from the Kerpage rehabilitation centre.

### **3.6.1 Population Characteristics**

The majority of the evaluation population were men, with quadriplegia resulting from spinal injuries (44%), the most prevalent age category was 20-30 years (44%), with varying degrees of educational qualifications. 71% of the subjects now live at home, their handicap was not recent, and 72% had some movement in their upper limbs. 59% used an electric wheelchair with normal hand controls. When using the robot 44% controlled it with a joystick or keyboard and 53% required specially adapted switches. The most frequently used tasks consisted of drinking (83%), using the phone, video, compact disc, audio, reaching, eating, brushing teeth, shaving, and brushing hair (16%).

### **3.6.2 Feedback from the Survey Subjects**

After conducting the clinical evaluation, the users were asked to prioritise the redesign and redevelopment work necessary for the system to meet their needs. These comments on the original design are given below together with their percentage values:

- 73% Development of appropriate user interfaces;
- 58% Development of more daily living and vocational tasks;
- 58% Cost reduction;
- 55% Design the system for attachment to a mobile base;
- 50% Design a wheelchair-mounted version of the system, and
- 25% Improve the aesthetics of the system.

## **3.7 CONCLUSIONS**

The data obtained through this survey has been an invaluable source of information upon which to base the design decisions. To a large extent this survey has verified, updated and expanded upon the Bath and other findings, and has also identified the needs and abilities of wheelchair-bound disabled people. By involving training and qualified occupational therapists in this project, it is hoped that some of these medical professionals have become educated to the possibilities of this new area of technology. Disabled people have been involved at the very beginning of this project so that the final design will be geared towards their needs and requirements. Every effort was made throughout the survey not to influence the subjects' answers, but without knowledge of

robotic devices, many subjects found it difficult to envisage what it would look like and how it could help them. In this respect our computer simulation video, showing the conceptual design performing various tasks was very useful (Prior, 1993b).

The fact that only 50 electric wheelchair users took part in the survey out of an estimated UK population of between 40,000-60,000 is a significant factor. However, these results have been shown to verify those of the earlier Bath study, the survey by Queen Margaret College and the French MASTER clinical evaluation, and are comparable in size with other surveys conducted in this country and in the USA. The widespread geographical distribution of the survey subjects (see Appendix A) should also justify the validity of the results. It is interesting to note that the survey subjects in both the Bath and MASTER clinical evaluations stated that they would like to see a wheelchair-mounted version of the workstation based system being developed in the future. This places further emphasis on the need and desire for wheelchair-mounted rehabilitation robotic manipulators.

A further survey is being conducted in British Columbia, Canada by the Arbutus Society for Children, using the questionnaire developed at Middlesex. This will prioritise the tasks of electric wheelchair users from the Canadian perspective. The Middlesex survey has identified the need for an assistive robotic aid for severely and very severely disabled people, and has also quantified the potential user population, with 84% of the survey subjects stating they would consider buying it.

The design specification for the robotic arm can only be compiled once the most appropriate tasks (for which the robotic arm is required to perform) have been determined. The design specification is a natural progression from the results of this section and is therefore contained in the following chapter.



# Chapter 4

## THE DESIGN SPECIFICATION

---

*'If you are in a shipwreck and all the boats are gone, a piano top bouyant enough to keep you afloat that comes along makes a fortuitous life preserver. But this is not to say that the best way to design a life preserver is in the form of a piano top.'*

*R. Buckmaster Fuller, 1969.*

---

### 4.1 INTRODUCTION

The design specification is the first step in the design process, whereby the wishes of the end user are translated into what can actually be accomplished. The specification is an integral part of the design process, that begins with the preliminary design specification (from which the system will evolve and develop) before culminating with the final design specification. The final design specification is not necessarily the last specification to be written, as this may have to be changed during the modification/redesign phase of the project.

In June 1989 a preliminary design specification was compiled, based on the initial results of the questionnaire survey, together with information gathered from disabled people, care specialists and medical rehabilitation staff. The preliminary design specification does not include references to any specific tasks that the robotic arm would have to undertake, as this information was not available at that time.

### 4.2 PRELIMINARY DESIGN SPECIFICATION

#### 4.2.1 Scope

- This specification covers the preliminary design requirements for an electric wheelchair-mounted manipulator for use by the physically disabled.

#### 4.2.2 Related Documents

- B.S. 5568 : 1978 Folding wheelchairs for adults.

### 4.2.3 Terminology

- The electric wheelchair shall be referred to as the 'wheelchair'.
- The electric wheelchair mounted manipulator shall be referred to as the 'system'.
- The 'operator', shall refer to the electric wheelchair user.
- 'Operation', shall refer to the control of the system either by direct control or by pre-programmed control.

### 4.2.4 General Requirements

- The system shall be capable of use by the majority of wheelchair users via several modular user interface options.
- The system shall have either a versatile end effector capable of picking up a large number of differently shaped objects or a tool changing end effector with an on-board selection of different end effectors.
- The operation of the system shall not require the use of any special skills.
- The system shall be capable of being mounted to as large a range of wheelchairs as possible without substantial modifications.
- The system shall be able to be fitted on either side of the wheelchair.
- The system shall be capable of either direct control by the operator through line of sight or by pre-programmed routines, it should also be capable of connection to a personal computer for workstation use.
- The system shall be capable of being easily detached from the wheelchair for either transportation or servicing.
- The operation of the system should not unduly fatigue the operator.
- The system shall be designed to be easy to manufacture, simple to assemble and also accessible for repair.

### 4.2.5 Design Requirements

- The system shall be capable of lifting 2 kg at maximum reach (see Section 2.3).
- The system shall have an absolute positional accuracy of  $\pm 5$  mm.
- The system shall have a coarse control speed of 0.2 m/s and a fine control speed of 0.05 m/s.
- The system shall be able to reach to a zone on the floor to the front and side of the wheelchair.
- The system shall be capable of reaching to a high shelf at a height of 2 m above the floor (maximum shelf reach of a 50<sup>th</sup>tile normal male adult)
- The system shall be capable of reaching to a zone in front of the operator from head to thighs.

- The system shall be designed to be stiff in the vertical plane.
- The system shall have a total weight of less than 25 kg (see Section 2.3).
- The system shall be designed to comply with B.S. 5568 (Folding Wheelchairs for Adults), regarding stability.

#### **4.2.6 Environmental Conditions**

- The system shall be capable of operation within a temperature range of 0-40 °C.
- The system shall be designed to prevent the ingress of dust and dirt.
- The system shall be constructed of materials able to withstand contact with chemicals and substances, which it might reasonably encounter in its working life.
- System noise levels are to be limited to 40 dB at 1 m.
- The system shall be primarily designed for use indoors.

#### **4.2.7 Ergonomics and Aesthetics**

- The system shall have a parked or home position which does not increase the overall size of the wheelchairs width or length.
- The systems power supply shall come from the wheelchair batteries and should enable the system to operate for periods amounting to at least 2 hr/day.
- The system shall be designed to conserve energy when static.
- The system shall be aesthetically designed, in terms of colour, texture and movement.

#### **4.2.8 Safety**

- The system when in operation shall be prevented from causing injury to the operator, by slow speed of operation, low inertia of moving parts, system monitoring and hard stops.
- An emergency stop switch and system reset should be provided.
- All external surfaces shall be free from sharp corners and projections.
- The system shall not unbalance the wheelchair when operating at maximum reach.

#### **4.2.9 Cost and Servicing**

- The system shall have a maximum component cost of £1,000 excluding the cost of interface mechanisms.
- The system shall have a mean time between failure of at least 3,000 hours.

The writing of the final design specification was undertaken in parallel with the development of the first prototype. The period between the preliminary and final design stages was approximately 18 months. During this time many changes from what was originally deemed necessary or essential were made. These changes can be seen in the final design specification below.

The positional accuracy of the arm was considered too high at  $\pm 5$  mm and was therefore reduced to  $\pm 15$  mm in line with the top eighteen tasks outlined in Table 3.2. The maximum reach height of 2.0 m was difficult to achieve and was therefore reduced to 1.7 m to allow the user the capacity to reach to the same maximum vertical reach as a 50 %tile male adult manual wheelchair user. By careful design the total weight of the system could be reduced from 25 kg to under 8 kg thus lowering the inertia and improving the stability of the wheelchair. By reviewing the top eighteen tasks it was found that the payload requirement of 2 kg could be further reduced to 1 kg thus reducing the torque requirements of the drive actuators.

Also included in this version are references to recently published standards for electric wheelchairs, developed over the last ten years by the American National Standards Institute in co-operation with the Rehabilitation Engineering Society of North America (RESNA) and the International Organization for Standardization committees (ISO).

The final design specification changed many times before reaching the current version as shown below (\* denotes changes):

## **4.3 FINAL DESIGN SPECIFICATION**

### **4.3.1 Scope**

- This specification covers the final design requirements for an electric wheelchair-mounted manipulator for use by the physically disabled.

### **4.3.2 Related Documents**

- B.S. 6937 : 1988 Glossary of wheelchair terms.\*
- B.S. 6936 : 1988 Method for designation of types of wheelchair.\*
- B.S. 6935 : Pt 5 1988 Wheelchair test - Methods for determination of overall dimensions, mass and turning space.\*
- ISO 7176 : Pt 1-13 Wheelchairs.\*
- ISO 554 Standard atmospheres for conditioning and/or testing specifications.\*

- IEC Publication 68-2-14 : 1974 Basic environmental testing procedures - Test N: change of temperature.\*
- IEC Publication 529 : 1976 Classification of degrees of protection provided by enclosures.\*

#### 4.3.3 Terminology

- The electric wheelchair shall be referred to as the 'wheelchair'.
- The electric wheelchair-mounted manipulator shall be referred to as the 'system'.
- The 'operator', shall refer to the electric wheelchair user.
- 'Operation', shall refer to the control of the system either by direct control or by pre-programmed control.

#### 4.3.4 General Requirements

- The system shall be capable of use by the majority of wheelchair users via several modular user interface options.
- The system shall have either a versatile end effector capable of picking up a large number of differently shaped objects or a tool changing end effector with an on-board selection of different end effectors.
- The operation of the system shall require minimal specialist training.\*
- The system shall be capable of being mounted to as large a range of wheelchairs as possible without substantial modifications.
- The system shall be able to be fitted on either side of the wheelchair with minimal modifications to the system.\*
- The system shall be capable of direct control by the operator through visual feedback together with reprogrammable memory locations for use with pre-programmed routines.\*
- The system shall be capable of connection to a personal computer for workstation use.
- The system shall be capable of being easily detached from the wheelchair for either transportation or servicing.
- The operation of the system should not unduly fatigue the operator.
- The system shall be designed to be easy to manufacture, simple to assemble and accessible for repair and servicing.\*

#### 4.3.5 Design Requirements

- The system shall be capable of lifting at least 1 kg anywhere within its working envelope.\*

- The system shall have a reach characteristic,  $r$ , of  $(0.7 < r < 0.9)$  m.\*
- The system shall have an absolute positional accuracy of  $\pm 15$  mm.\*
- The system shall have a repeatability of  $\pm 10$  mm.\*
- The system shall have a coarse control speed of 0.2 m/s and a fine control speed of 0.05 m/s for the end point velocity.
- The system shall be able to reach to a zone on the floor, to the front and side of the wheelchair.
- The system shall be capable of reaching to a maximum height of 1.7 m above the floor.\*
- The system shall be capable of reaching to a zone in front of the operator from head to thigh (normal operating mode).
- The system shall be designed to have a kinematic configuration which under normal use is stiff in the vertical plane and compliant in the horizontal plane.\*
- The system shall have a total weight of less than 8 kg.\*
- The system shall be designed to comply with ISO 7176 : Part 1 : Determination of Static Stability, and ISO 7176 : Part 2 : Determination of Dynamic Stability of Electric Wheelchairs.\*
- The system shall be designed and programmed with reference to the top eighteen tasks listed in chapter 3.5.\*

#### 4.3.6 Environmental Conditions

- The system shall be capable of operation within a temperature range of 0-40 °C.
- The system shall be designed to prevent the ingress of dust and dirt.
- The system shall be constructed of materials able to withstand contact with chemicals and substances, which it might reasonably encounter during it's working life.
- System noise levels are to be limited to 40 dB at 1 m.
- The system shall be designed for both indoor and outdoor use.\*
- The system shall be designed to comply with ISO 7176 : Part 9 : Climatic Tests for Electric Wheelchairs.\*

#### 4.3.7 Ergonomics and Aesthetics

- The system shall have a parked or home position which does not substantially increase the overall size of the wheelchair's width or length.
- The system's height when parked shall be below the height of the wheelchair's armrest.\*
- The system shall not prevent the wheelchair from passing through a normal doorway (see Section 1.3.2).\*



- The system's power supply shall come from the wheelchair's batteries.
- The system shall be capable of continuous operation for at least 4 hr/day.\*
- The system shall be designed to conserve energy when static.
- The system shall be aesthetically designed, in terms of form, size, colour, texture and movement.\*

#### **4.3.8 Safety**

- When in operation the system shall be prevented from causing injury to the operator by employing slow speed of operation, low inertia of moving parts, system monitoring and hard stops.
- An emergency stop switch and system reset switch should be provided.
- All external surfaces shall be free from sharp corners and projections.
- The system shall not unbalance the wheelchair when operating at maximum reach.

#### **4.3.9 Cost**

- The system shall have a maximum component cost of £1,500 - excluding the cost of interface mechanisms.\*

#### **4.3.10 Life Expectancy and Servicing**

- The system shall not require maintenance for at least the first 500 hours use, with an annual service thereafter.\*
- The system shall have a total life of at least 6,000 hours.\*

### **4.4 CONCLUSIONS**

A comparison of the two specifications shows that the final design specification is a much looser one than the earlier preliminary design specification. The reasons for this are mainly due to the lessons learned during the first prototype design stage, ie that the positional accuracy could be relaxed and that the height requirement of 2 m was difficult to achieve. The specification for the total weight of the arm was lowered from 25 kg to less than 8 kg, this has led to the use of materials such as aluminium alloy, stainless steel and composites. The payload was also halved, to 1 kg thus lowering the joint torque requirements.

The arm's reach requirement is determined by the wheelchair dimensions and the requirement to be able to reach to the floor. This inevitably causes large inertial forces and bending moments, which if the mass of the arm was large would cause serious

safety implications. The goal was to make the arm light, of small section and as inconspicuous as possible when not in use, whilst still meeting the performance criteria. It is envisaged that the arm would be covered with some form of material which could be easily removed and washed. This material could also include padded regions which would act as a safety feature.

The final design specification includes a requirement for both direct control and computer augmented control, which would enable memory locations to be saved and replayed. This would also provide safety features such as system monitoring and control over the joint speeds and positions. This was found to be an essential requirement for a wheelchair-mounted manipulator and the absence of this feature was the main reason why many previous systems failed.

The system should be able to be operated indoors and outdoors, giving the user more freedom. However, it was not envisaged that the arm would be used in harsh environmental conditions such as heavy rain, just as it is true that electric wheelchair users would not subject themselves to operate under similar conditions.

The design should be capable of a longer period of continuous daily use and have a longer life span. It is very important to give the purchaser of the system a low cost/high benefit ratio, especially since the largest purchaser of such a system would be a local health authority.

In summary, the final design specification has simplified the design of the system by relaxing unnecessarily tight requirements. It also recognised the need to give the consumer more value for money in terms of operation and product life cycle.

The following chapter reviews the human muscle system and discusses past and present attempts to mimic its function by the use of artificial muscle equivalents. The flexator pneumatic muscle actuator is introduced and its performance compared with other forms of direct-drive actuator. Finally, the performance characteristics of single and dual flexator actuators are given and the results of an ACSL program to simulate the dual flexator system is presented.

# Chapter 5

## HUMAN MUSCLE AND ITS ARTIFICIAL EQUIVALENT

---

*'Under the spreading chestnut tree the village smithy stands; the smith, a mighty man he is, with large and sinewy hands; and the muscles of his brawny arms are strong as iron bands.'*

*Henry Wadsworth Longfellow, c 1860.*

---

### 5.1 INTRODUCTION

Human muscles are connected at either end to bone, and relative movement of a joint is achieved by the ability of the muscle to contract. For example, when the elbow joint is moved, both the biceps and triceps muscles are activated, one is contracting and the other is relaxing, this coactivation allows a smooth transition between joint angles and also allows for a far greater degree of control of the compliance of the limb (Edholm, 1967). The speed and force of the resulting contraction can be varied and controlled due to the fact that the muscle consists of many thousands of fibres, with each nerve fibre activating a given quantity of the muscle fibres. By varying the number of nerve impulses, the contraction of the muscle can be controlled, together with the applied force. Each muscle and joint system has a complex and elaborate series of feedback loops which inform the brain of the joint position and the force being exerted. This feedback is essential for controlled, smooth and accurate movement of the limb (see figure 5.1).

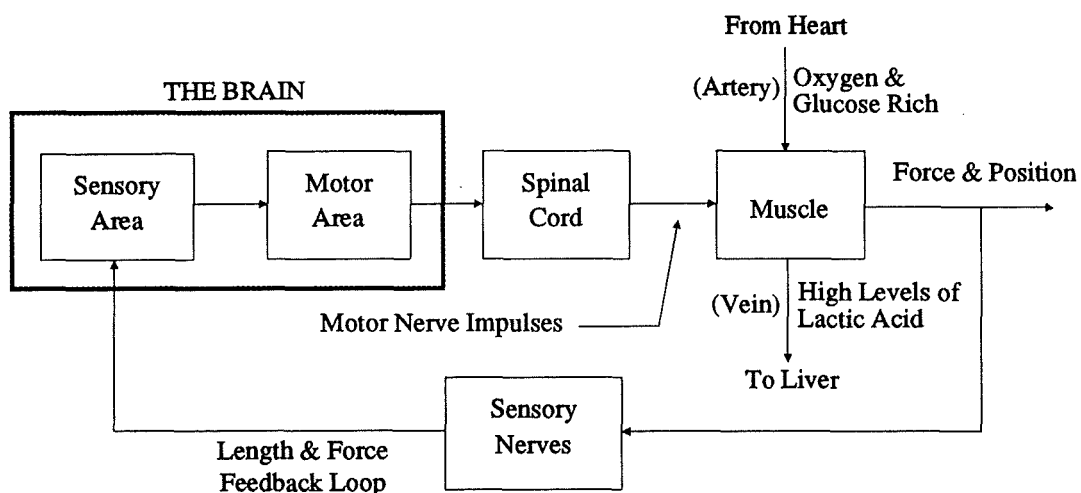


Figure 5.1 - Human muscle control circuit and feedback path.

Human muscles are defined by Haggard (1946) as 'machines burning carbonaceous fuel at low temperatures', which convert chemical energy to mechanical energy. Muscles derive their chemical energy from foodstuffs which consist primarily of carbohydrates, glycogens and fatty acids. These are first broken down to form lactic acid (the anaerobic process) and then to carbon dioxide and water (the aerobic process). If lactic acid accumulates in the muscle, its action declines and finally stops, causing cramp. The anaerobic process is a short-term energy supply system designed to allow time for increased levels of oxygen entering the blood stream, to reach the muscle. An active muscle requires twenty times as much oxygen as an inactive one, and to supply this level, the blood flow must be increased accordingly.

From equation 5.1, human muscle can be shown to have a peak efficiency of approximately 45% (Hogan, 1984) and an average efficiency of about 22% (Wilkie, 1960; Young, 1971) (see figure 5.2).

$$\eta = \frac{P_m}{P_c} = \frac{F_o^2}{P_c b} \left(1 - \frac{F}{F_o}\right) \frac{F}{F_o} \quad (5.1)$$

Where  $P_m$  is the mechanical output power;  $P_c$  is the chemical input power;  $F$  is the relative muscle force;  $F_o$  is the isometric muscle force and  $b$  is the viscous friction constant of the joint.

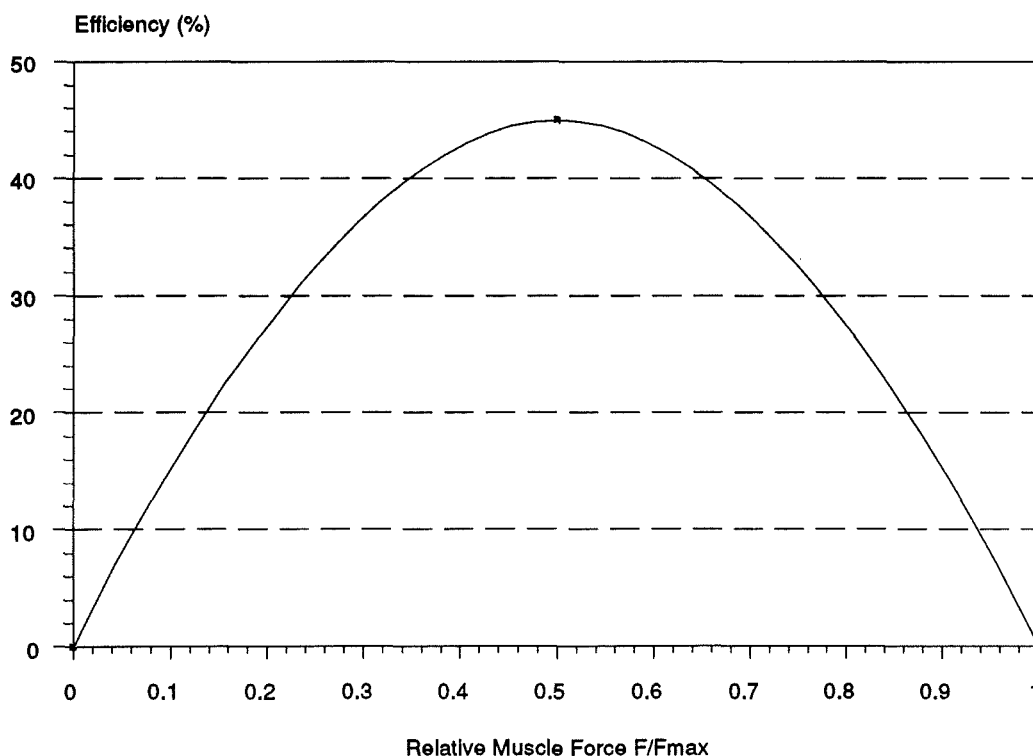


Figure 5.2 - Relationship between efficiency and force ratio

To achieve maximum efficiency, the force and the speed of movement must be suitably matched, this is achieved at approximately 50% of the maximum force and 25% of the

maximum velocity of movement. From physiological research conducted by Wilkie (1960), 1 kg of muscle can develop about 0.22 kW of power, since the average adult male has about 40% muscle by weight. This means that there exists a theoretical power output of approximately 6.89 kW of power; however, this would involve all the muscles of the body in a single contraction against a suitable load, which clearly is impossible. Since most muscles are grouped into antagonistic pairs, the absolute theoretical power output comes down to about 3.44 kW. This level of power output can only be sustained for a very short period of time, this is due to the small reservoir of available energy stored in the muscle fibre as glycogen. If the work effort is maintained for longer periods, the power output falls exponentially to about 746 W at the end of one minute and then more slowly to about 373 W in five minutes. At this level of output, activity can be maintained for approximately 2 to 2.5 hours as required by marathon runners (see figure 5.3). The max power output for an average arm can be calculated as about 300 W.

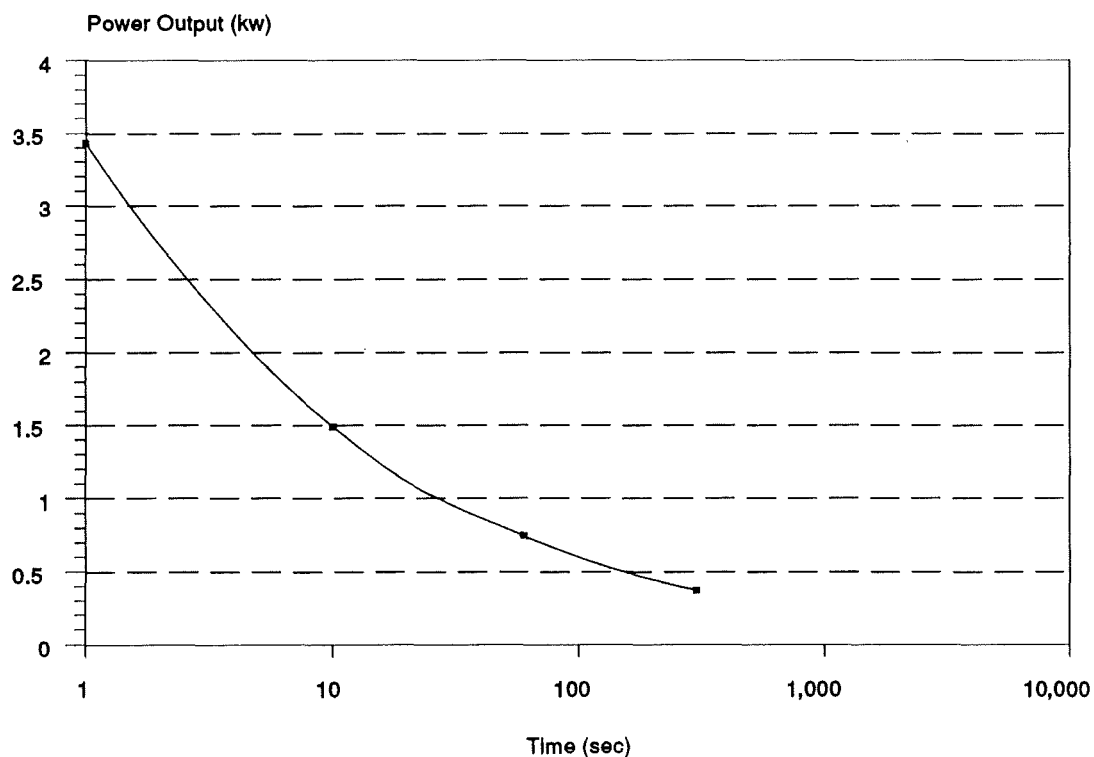


Figure 5.3 - Endurance performance of human muscle (Wilkie, 1960).

### 5.1.1 Pneumatic Muscle Type Actuators

Previous work on powered prosthetics/orthotics and rehabilitation robotics has focused on the use of conventional forms of actuation, mainly via electric servo motors. However, pneumatic muscle actuators which imitate human muscle appear to offer many benefits over these more traditional actuators especially when used in these specific application areas.

Pneumatic muscle actuators have been in existence for over 35 years, one of the first to be developed being the McKibben artificial muscle (Schulte, 1961) which was used as the actuator in a powered orthosis at the Rancho Los Amigos hospital, Los Angeles (see figure 5.4). This type of actuator was driven by compressed CO<sub>2</sub> gas at pressures up to 6 bar and tests were conducted to investigate the static and dynamic performance of the muscle in a uni-directional prismatic arrangement. This device consisted of a longitudinal piece of hollow braided material, a gas tight inner tube and suitable end fixtures for external attachment and pressurization. When pressurized, the braided material expanded and the axial length contracted, so exerting a tension,  $T$  (N) as defined in equation 5.2 by Takamori (1991).

$$T = \frac{\pi D_o^2 P}{4} \cdot \frac{3(1 - \epsilon)^2 \cos^2 \theta - 1}{\sin^2 \theta_o} \quad (5.2)$$

Where  $P$  is the pressure,  $\epsilon$  is the contraction ratio,  $D_o$  is the diameter of the actuator at  $P=0$ , and  $\theta_o$  is the cross angle of the twisted fibre. For simplicity this equation does not take into account the elastic or frictional effects of the material.

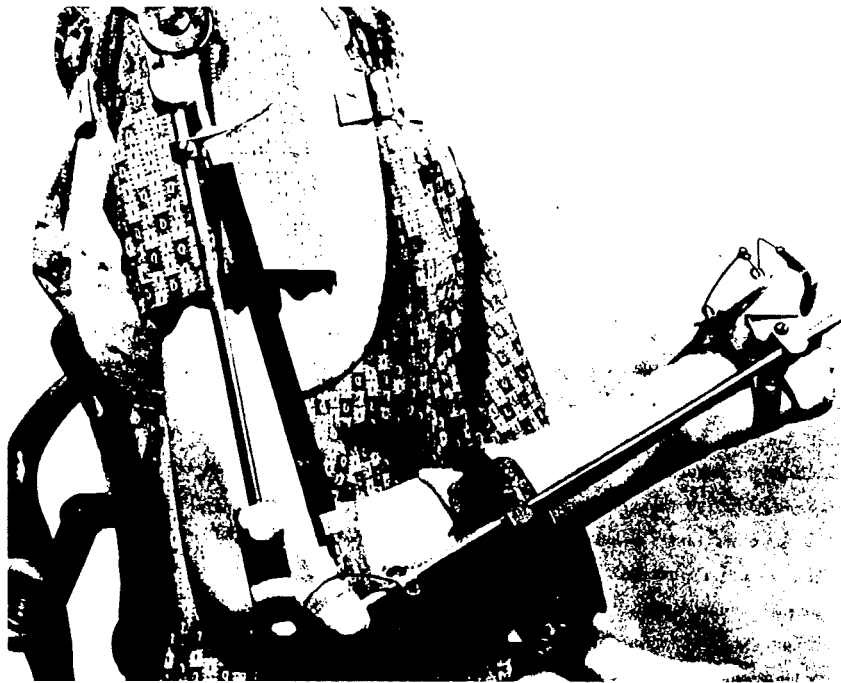


Figure 5.4 - The McKibben artificial muscle.

Since the early experiments with the McKibben actuator (Engen, 1964-67; Gavrilovic & Maric, 1969; Baldwin, 1969), the use of pneumatic muscle actuators declined, until their reemergence in 1984 when the Bridgestone Corporation in collaboration with Hitachi brought out their 'Rubbertuator' pneumatic muscle actuator, based on the earlier work of Uno & Sakaguchi (1969), which was used to power a seven degree of freedom robot arm designed for assembly line work (EPW, 1984).

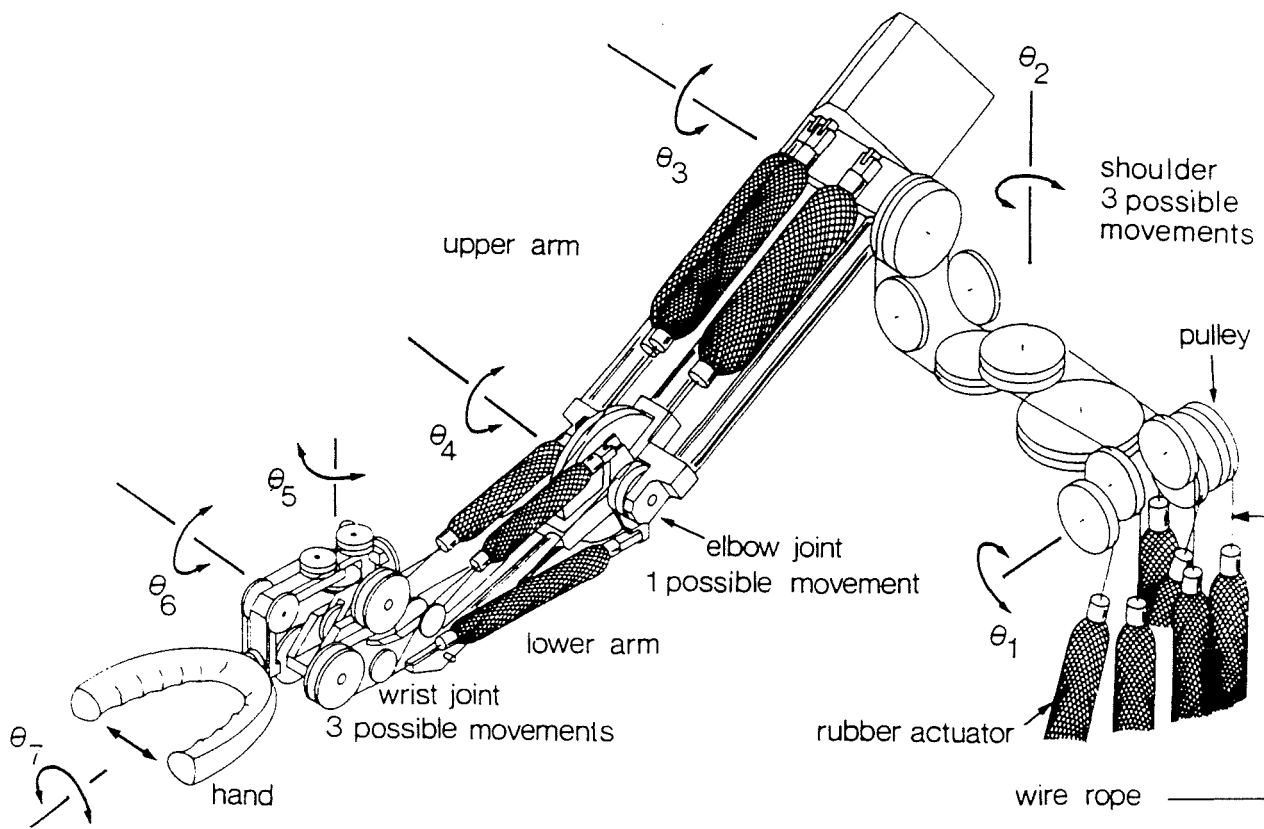


Figure 5.5 - Rubbertuator driven Bridgestone/Hitachi robot.

The principle of operation of the 'Rubbertuator' was based on the earlier McKibben artificial muscle. The arm weighing only 6 kg had a high power/weight ratio and could lift a mass of 2 kg (see figure 5.5). However, the design was not commercially exploited.

In 1986 MacDonald Dettwiler & Associates Ltd of Vancouver developed the ROMAC system (RObotic Muscle ACtuator) (Immega, 1986; Grodski & Immega, 1988), again the principle of operation was the same as the McKibben muscle.

The structure consisted of an articulating bladder, a steel wire mesh enclosure and end

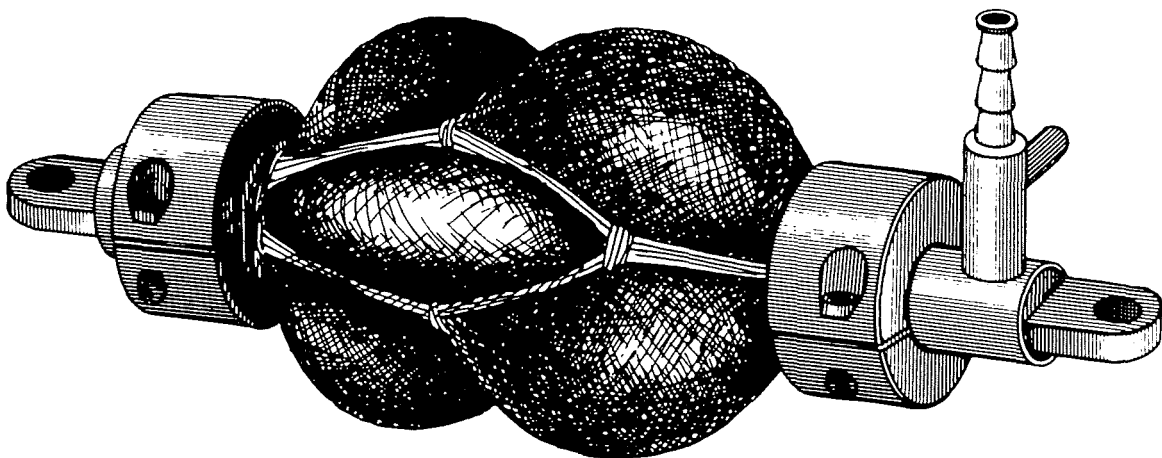


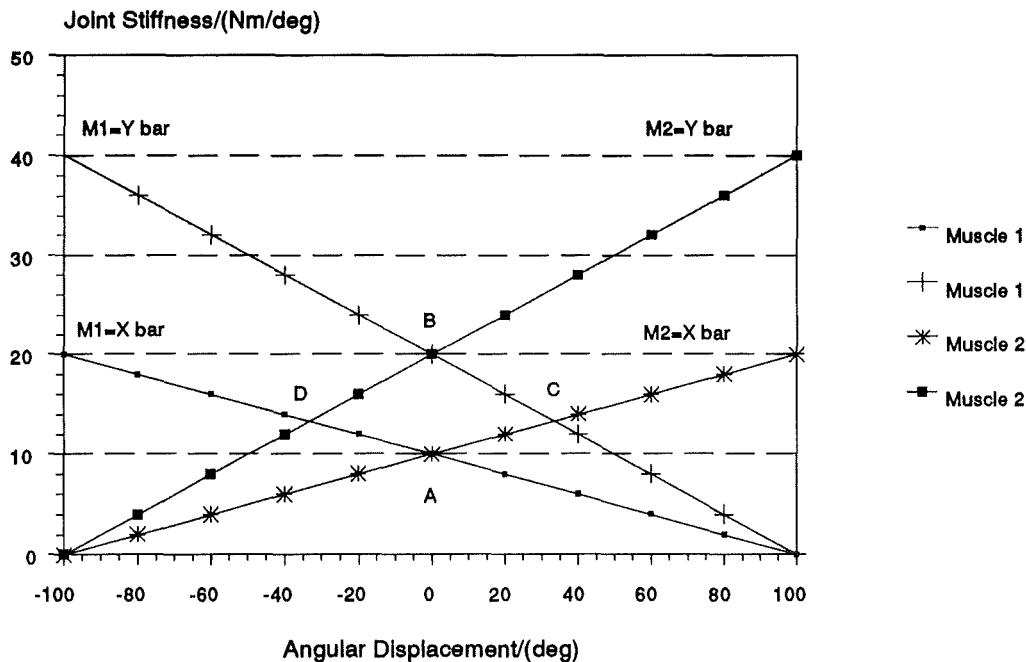
Figure 5.6 - ROMAC actuator with arcuate lobes.

fittings. An inelastic bladder was used which had a constant surface area and could expand in volume while contracting axially (see figure 5.6). This system used compressed air at 7 bar and could contract by up to 50% of its original length, developing a maximum force of 1500 N for the 0.2 m long actuator. A standard range of actuators was manufactured using woven Kevlar and DuPont Hytrel. Work to weight ratio compared to a conventional pneumatic cylinder of similar area was stated to be 20:1.

### 5.1.2 Controllable Compliance

The ability to control compliance using antagonistic pairs of pneumatic actuators was postulated, based on the earlier research work of Gavrilovic & Maric (1969), Hogan (1984) and Winters et al (1988), who investigated the role of human antagonistic muscle groups in modulating mechanical impedance of joints.

In the ROMAC system, by increasing the pressure in a pair of pneumatic actuators whilst maintaining the pressure ratio, the angular position of the arm is maintained, but its compliance decreases. Figure 5.7 illustrates the principle of controllable compliance. A pair of pneumatic muscles, M1 and M2 are used to operate a double-acting rotary joint. If M1 and M2 are pressurized to X bar then the joint will be at the neutral position and will have a stiffness of 10 Nm/deg (point A). The stiffness of the system can be increased to 20 Nm/deg whilst maintaining its position by increasing the pressure in both M1 and M2 to Y bar (point B). Each point of intersection of a line on the graph represents a unique pressure ratio and hence an angular position and stiffness (points C and D).



X bar < Y bar

Figure 5.7 - Controllable compliance of antagonistic muscles



and D). Therefore if it were possible to infinitely control the pressure ratio of the two muscles, it would be possible to vary the position of the joint and control its compliance. It should be stated that the above description is an idealised case, without the problems caused by non-linearities in actual systems.

A closer approximation to the human control strategy can therefore be achieved using antagonistic pairs of pneumatic muscles which provide a more human-like feel. The most recent work in this area has been carried out by Winters (1990) at Arizona State University, investigating McKibben and other types of pneumatic muscle actuators for applications in prosthetics and orthotics.

### 5.1.3 External Power Source Criteria

The criteria for any external power source were set out in 1960 by Kiessling (1961), these were defined as:

- Universally available;
- Low cost;
- Non toxic;
- Safe in use;
- Ease in handling;
- Portable, and
- High power/weight ratio.

Electric servo motors certainly fulfil some of the above criteria. However, in the areas of low cost and high power/weight ratio they cannot compete with other forms of actuation, such as pneumatic muscle actuators.

### 5.1.4 The Flexator™ Pneumatic Muscle Actuator

The flexator pneumatic muscle actuator described here was invented by Mr Jim Hennequin of Airmuscle Ltd. The flexator is constructed from standard lay-flat fire hose material, manufactured in the UK for fire fighting applications.<sup>1</sup> The fire hose material consists of a smooth, ozone-resistant synthetic rubber lining and a high tenacity Polyester jacket. The fire hose is manufactured in standard sizes from 42 mm flat width to 120 mm flat width, and has a minimum burst pressure of 24 bar for the largest sized hose. The mass/unit length ranges from 0.23 kg/m to 0.64 kg/m and the cost/metre length is approximately £3.00.

1 - British Standard 6391 : 1983 'Non-percolating layflat delivery hoses and hose assemblies for fire fighting purposes.'

### 5.1.4.1 Design advantages of using flexators

- Low cost;
- Low mass;
- Readily available;
- Maintenance free;
- Finite actuator stroke;
- Cold/Heat resistant, and
- Anti-rot.

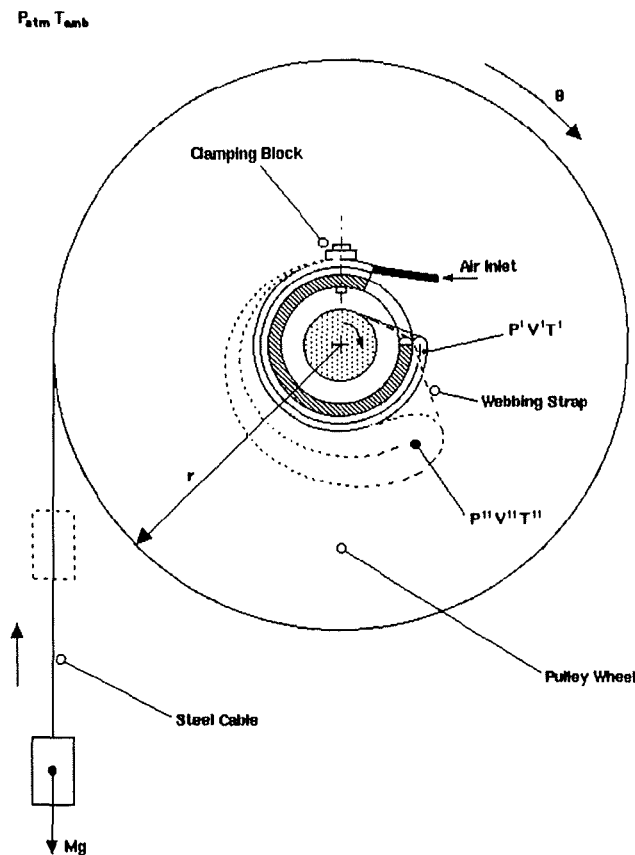


Figure 5.8 - Flexator rotary actuator experimental test-rig.

A flexator rotary actuator is produced by cutting the desired length of fire hose, then folding it in two and sealing the inlet pipe into one of the ends and clamping both ends to the outside surface of a tube (see figure 5.8). The flexator is held against the tube by a webbing strap which is in turn clamped to the tube at one end and then passes through a window cut into the tube and is attached to a shaft which rotates in ball (roller) bearings. When the muscle is pressurized, its volume increases and thus the webbing strap is unwound from the shaft. The angular displacement of the shaft,  $\theta$ , is a function of the load torque,  $T_L$  (Nm), the final flexator gauge pressure,  $P^{II}$  (bar), the final flexator volume,  $V^{II}$  ( $m^3$ ), and the system efficiency,  $\eta$ .

$$\theta_{rad} = f(T_L, P^{'' gauge}, V^{''}, \eta) \quad (5.3)$$

Equation 5.3 assumes that the process is adiabatic (no heat transfer), the initial volume of the flexator is zero and that the initial pressure of the flexator is atmospheric.

#### 5.1.4.2 Experimental testing (Prior, 1993b)

The flexator has been tested extensively in the rotary configuration using a purpose-built single-axis test-rig incorporating potentiometric measurement of angular position, measurement of line and flexator pressure and also internal flexator air temperature.

The experimental analysis involved the static and dynamic performance measurement of the flexator in twelve configurations, varying the length and width of the muscle, with all twelve configurations being tested on the same test-rig. When pressurized, the flexator experiences a constant load torque,  $T_L$  which is dependent upon the suspended mass,  $M$  (see Table 5.1).

**Table 5.1 - Summary of Static Test Results.**

(flexator pressure at 3.5 bar gauge; output shaft  $\phi$  30 mm)

| 42 mm                                  | 60 mm                                  | 83 mm                                  | 102 mm                                  | Width<br>Length                            |
|--|--|--|---|--|
| 0.67 Nm ~ 235 deg<br>2.33 Nm ~ 118 deg | 1.22 Nm ~ 245 deg<br>5.65 Nm ~ 114 deg | 2.33 Nm ~ 284 deg<br>8.98 Nm ~ 79 deg  | 3.44 Nm ~ 267 deg<br>10.09 Nm ~ 118 deg | 90 mm<br>( $\gamma = 2.827 \text{ rad}$ )  |
| 1.22 Nm ~ 284 deg<br>3.44 Nm ~ 85 deg  | 3.44 Nm ~ 285 deg<br>6.76 Nm ~ 99 deg  | 6.76 Nm ~ 282 deg<br>11.20 Nm ~ 95 deg | 8.98 Nm ~ 268 deg<br>13.41 Nm ~ 90 deg  | 130 mm<br>( $\gamma = 4.084 \text{ rad}$ ) |
| 1.22 Nm ~ 295 deg<br>4.55 Nm ~ 80 deg  | 4.55 Nm ~ 305 deg<br>7.87 Nm ~ 134 deg | 8.98 Nm ~ 287 deg<br>12.30 Nm ~ 93 deg | 11.20 Nm ~ 300 deg<br>15.63 Nm ~ 53 deg | 170 mm<br>( $\gamma = 5.341 \text{ rad}$ ) |

#### 5.1.4.3 Flexator hysteresis and non-linearity

The flexator when used in the single muscle configuration exhibits a large degree of hysteresis and non-linearity as can be seen from a typical flexator test result (see figure 5.9 and Appendices F1, F2). It is proposed that this effect can be reduced by careful selection of the flexator width in relation to the outside diameter of the outer tube, having limited strokes and by using non-elastic materials for the flexator and webbing straps (see Section 5.6).

# Single Flexator Static Test

Flexator Type and Position: 60 x 90 ; 5

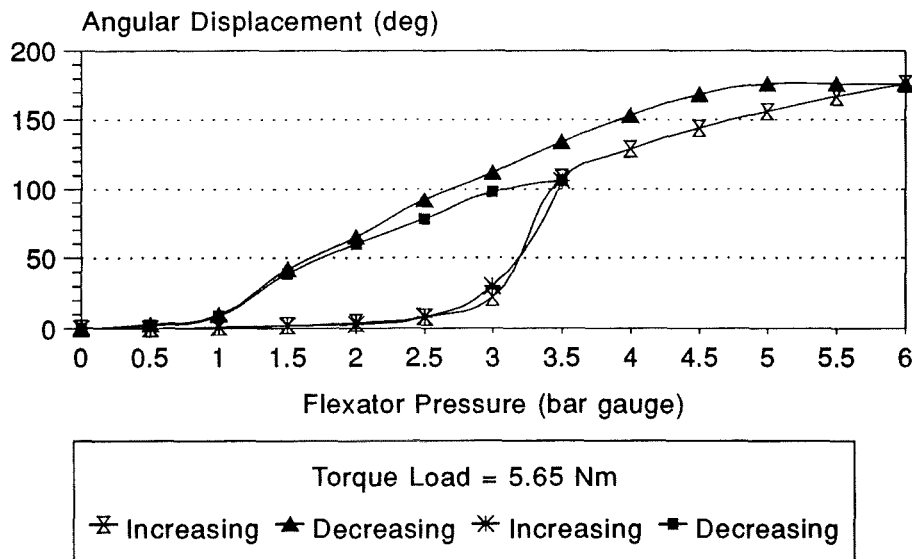


Figure 5.9 - Static test showing non-linearity & hysteresis.

Pneumatic muscle type actuators like the flexator offer distinct advantages over the more conventional forms of actuation. The flexator seems ideally suited to the field of rehabilitation robotics because of its low-cost, low mass, compliant behaviour, its ability to work in limited arcs of movement, and the fact that it can conserve energy when static. When used in antagonistic pairs, they can provide double-acting control together with an ability to vary joint compliance independently of joint angle in a similar manner to human muscles.

The problems associated with this type of actuator, as with all pneumatic devices, center on their inherent non-linearity and the difficulty to accurately control position. The non-linear properties are mainly caused by the creep of the elastic materials used and the friction losses, the positional control problem is due to the compressibility of the medium.

In the context of a rehabilitation manipulator, compliance can be said to be a safety feature, giving soft actuation. The problems of positional control can be overcome by using flexator rotary actuators for the coarse movement of the arm, whilst allowing the fine movement of the end effector to be controlled by small electrical stepper motors.

## 5.2 COMPARATIVE PERFORMANCE OF THE FLEXATOR WITH OTHER FORMS OF DIRECT-DRIVE ROTARY ACTUATOR

Several reviews of industrial robots conducted over the last decade have shown the general trend towards electrical servo drives in preference to both pneumatic and hydraulic methods of actuation (Biscoe & Mills, 1988; Cakebread, 1982; Considine, 1986; Pera, 1981). From these surveys the percentage methods of actuation have been found to be: electrical drives - 50%, pneumatic drives - 20%, and hydraulic drives - 15%. With the remaining 15% utilising a mixture of more than one type of drive.

A general comparison between electrical, hydraulic and pneumatic forms of actuation has shown that pneumatic actuators have distinct advantages over the other two in terms of cost, mass and safety, and comparable performance in terms of power to weight ratio and ease of use (Plettenburg, 1989; Pellerin, 1992). The main disadvantages of pneumatic actuators lie in their poor controllability, sluggish response under high load and inherent non-linearity (Young, 1971).

Table 5.2 - Comparison of Electrical, Hydraulic and Pneumatic Actuation.

| Evaluation Criteria   | Electrical Actuation | Hydraulic Actuation | Pneumatic Actuation |
|-----------------------|----------------------|---------------------|---------------------|
| Cost                  | Medium               | High                | Low                 |
| Power to Weight Ratio | Medium               | High                | Medium to High      |
| Driving Force         | Small to Medium      | Large               | Medium              |
| Controllability       | Good                 | Fair                | Poor                |
| Responsiveness        | High                 | High                | Medium              |
| Safety                | Fair                 | Poor                | Good                |
| Ease of Use           | Good                 | Fair                | Good                |

The Peak Torque to Motor Mass Ratio ( $T_p/MM$ ) is the reciprocal of a performance ratio used by Asada et al (1981) to rate direct-drive DC torque motors. This ratio gives an indication of the performance of an actuator and has been used throughout this assessment to rate the performance of different types of actuation without consideration for any additional components or controlling units (see Appendix B1/2).

### 5.2.1 Conventional Pneumatic and Hydraulic Rotary Actuators

Conventional pneumatic and hydraulic rotary actuators come in three basic types, rotary vane (single or double), rack and pinion (single or double) and helical planetary. Each system has its own advantages and disadvantages which are described below.

### 5.2.1.1 Vane type rotary actuators

Rotary vane type pneumatic actuators consist of single or double vanes mounted on a drive shaft and enclosed by an airtight chamber. By varying the pressure differential across the vane(s), the actuator can produce rotary motion. For a given size of actuator the output torque can be doubled by increasing the number of drive vanes from one to two; however, this has the effect of reducing the angular output,  $\theta$  from about  $280^\circ$  to about  $100^\circ$  (see figure 5.10). Equation 5.4 gives the formula for calculating the output torque of a single vane actuator in terms of its pressure differential, effective vane area and the effective radius of the vane.

$$T_q = (P_1 - P_2) A_e R_e \quad (5.4)$$

Where  $T_q$  is the output torque of the actuator,  $P_1$  is the pressure in chamber 1,  $P_2$  is the pressure in chamber 2,  $A_e$  is the effective area of the vane and  $R_e$  is the effective radius of the vane from the centre of the output shaft. Pneumatic vane type actuators usually operate at air pressures up to 6 bar absolute and can have output torques of up to 6,000 Nm. The hydraulic vane type actuator can operate at up to 210 bar and can develop torques of up to 83,000 Nm. Actuators designed specifically for opening valves in the chemical and process industries have an operating stroke of  $90^\circ$  and an output torque of up to 5,000 Nm. Control of vane type actuators is achieved mainly via adjustable end stops (bang-bang control), without intermediate position control. However, a complete range of additional accessories is generally available, which consist of position transducers, limit switches, spring return units, integral solenoid valves and flow control

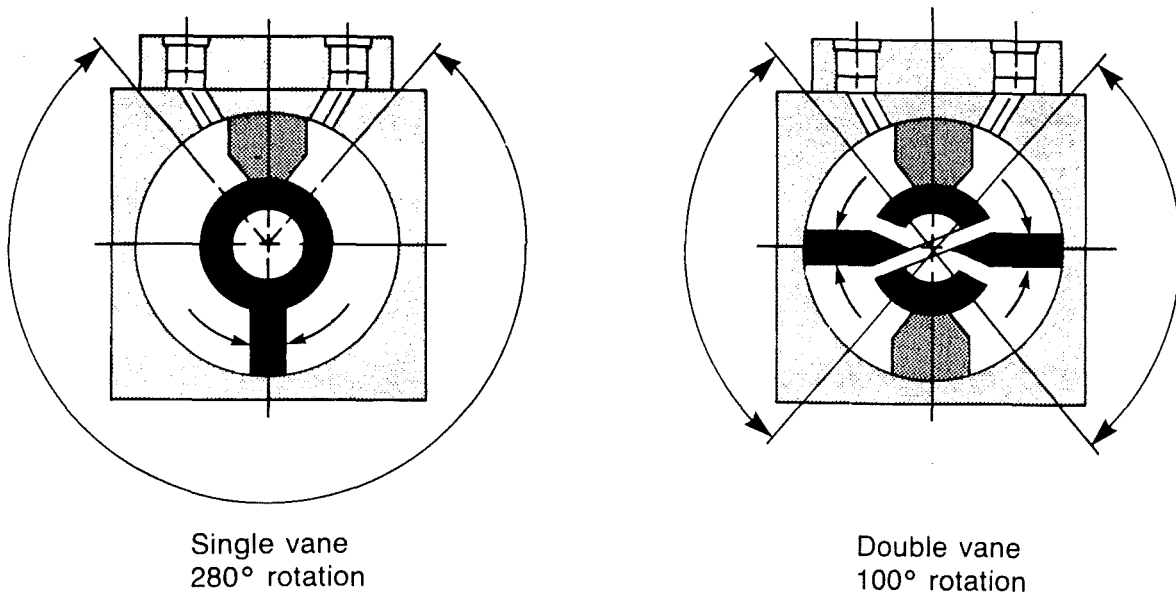


Figure 5.10 - Vane type rotary actuator.

valves, where greater accuracy is required. Because of their simple construction and low number of parts, rotary vane type actuators can be of low cost, high torque to mass ratio and can have a long maintenance-free life. The main problems with this type of actuator are associated with the vane sealing arrangement which if too tight will cause excessive stiction and if too loose will cause excessive leakage and loss of pressure. The physical size of the actuator (if high torques are required) becomes unacceptably large as indicated by equation 5.4. As mentioned previously, control of intermediate positions is also a reason why this type of actuator is not more widely used in the automation field.

### 5.2.1.2 Rack & pinion type rotary actuators

This type of actuator converts linear movement of a piston into rotary motion of the output shaft by the use of a rack and pinion gear arrangement as shown in figure 5.11. These units can consist of either single or double racks, with the double rack system being able to output twice the torque of the single rack. Variations of this arrangement can be found whereby the pistons of a double rack and pinion unit are hollow, thus transmitting fluid pressure to internal drive piston faces. This arrangement has the advantages of: allowing the inlet and exhaust ports to be mounted at the same end of the actuator, maintaining meshing of the rack and pinion gearing, (thus preventing backlash), and improving the actuator efficiency.

Pneumatic rack and pinion type actuators operating at 6 bar can output torques of up to 5,000 Nm, with the newer types having high torque to mass ratios (see Appendix B1).

Operating principle

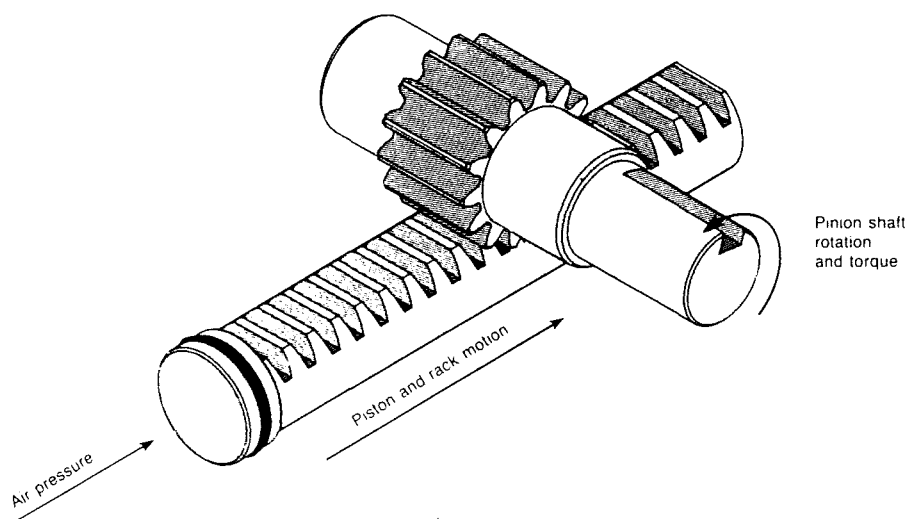


Figure 5.11 - Rack & pinion type rotary actuator.

The disadvantages of this type of actuator centre on the sealing arrangement of the piston(s), the large overall size and mass of the actuator together with the fact that the design has more components than the simpler vane type actuator, and is therefore more expensive.

### 5.2.1.3 Planetary helical type rotary actuators

A recent development in the field of rotary actuators, the planetary helical type actuator (Hope, 1992) is basically a helical actuator but with rolling elements rather than sliding splines. There are only two moving elements: the piston assembly which reciprocates and rotates within the housing and the shaft which only rotates. The piston moves in and out as the fluid pressure is ported to one side or the other. As the piston is displaced axially, its rollers follow the helical grooves in the housing and on the shaft, forcing the concurrent rotation of the shaft. The grooves on the shaft and housing are of opposite hand, and hence the rotation is compounded (see figure 5.12). This type of actuation can be driven by either hydraulic or pneumatic power. The pneumatic type actuator operating at 6 bar can produce 125 Nm, with the hydraulic version operating at 200 bar able to output 3,000 Nm. Advantages of this type of actuator are that there is negligible backlash, as in conventional gear assemblies, large load carrying capacity is possible and hollow drive shafting means that cabling and piping can be carried through the centre of the actuator. The stroke of the actuator can also be varied at the time of manufacture between 0° and (180° or 360°). However, the performance ratio for this type of actuator



Figure 5.12 - Planetary helical rotary actuator (Helac©).



is not as high as the hydraulic vane type actuator. The design is complicated and hence the overall cost is relatively high. However, the performance ratio of this type of actuator when used with hydraulic fluid reaches similar values to the hydraulic vane type actuator.

### 5.2.2 Conventional Electrical Rotary Actuators

As previously mentioned electrical drives are found in approximately 50% of industrial robots. With the trend towards light, fast, direct-drive robots this figure is likely to rise even higher in the future (Pal, 1991).

The most commonly used electrical rotary actuator is the dc motor; other devices include the dc rotary solenoid, this will be described later. The term dc motor incorporates a myriad of different forms of electrical drive, ie wound field, reluctance, or permanent magnet. These main types can then be subdivided into other forms such as, brushed, brushless, stepper, etc (Huntingford, 1988). Electrical dc motors typically operate at high speeds and output low torques, they are therefore used predominantly in combination with a gearbox.

The dc motor consists of an armature with a commutator winding rotating within a uni-directional electromagnetic field. The field can be connected in three different ways:

- (a) Separately from the armature - *Separate excitation*.
- (b) In parallel with the armature - *Shunt excitation*.
- (c) In series with the armature - *Series excitation*.

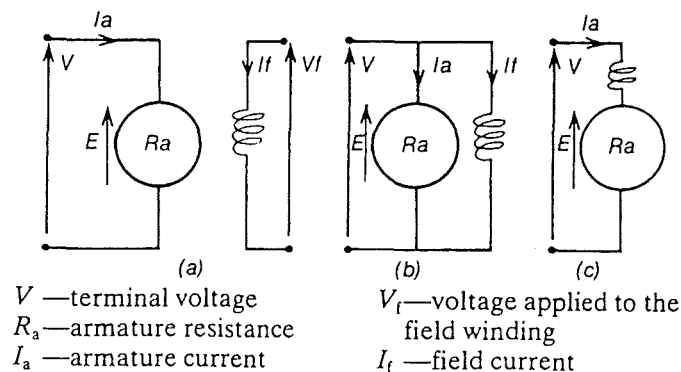


Figure 5.13 - DC motor excitation (Whitehead, 1991).

The induced voltage,  $E$  in figure 5.13 is proportional to the speed of rotation of the armature,  $\omega$  and the amount of magnetic flux,  $\Phi$  produced by the field winding.

$$E = k \omega \Phi \quad (5.5)$$

For any given machine:

$$k = 2p Z_s \quad (5.6)$$

Where  $2p$  is the number of magnetic poles on the field winding and  $Z_s$  is the number of armature conductors connected in series.

The governing equation for the dc motor is thus:

$$V = E + I_a R_a \quad (5.7)$$

Multiplying by  $I_a$  gives:

$$V I_a = E I_a + I_a^2 R_a \quad (5.8)$$

Where  $V I_a$  is the input power,  $I_a^2 R_a$  is the power loss in the armature resistance and  $E I_a$  is the mechanical power output.

If  $T_m$  is the motor torque, then  $E I_a = T_m \omega$ , and.

$$T_m = \frac{E I_a}{\omega} = k I_a \Phi = 2p Z_s I_a \Phi \quad (5.9)$$

Each type of dc motor exhibits a unique speed-torque relationship which has benefits to certain application areas. Electrical motors used in robotics range from about 25-250 W, with the main requirements being that their speed-torque or angle-torque characteristics are approximately linear and that they can operate bi-directionally (Whitehead, 1991).

#### 5.2.2.1 Permanent magnet dc servo motors

These types of motor operate on the principle of the separately excited dc motor. The armature circuits have been developed to exhibit low inertia and inductance, and so produce a fast response. Mechanical time constants of less than 5ms are possible, which are comparable with hydraulic motors (Mannetje, 1981). Due to constructional differences, several proprietary types have been developed, some of these are listed below:

*The printed circuit board motor* - has an armature winding which was originally etched onto a printed circuit board (hence the name). The latest design of this type of motor utilises a stamped armature disc with approximately 100 conductors. Since the armature does not contain iron, the inertia and inductance are very low and this results in a fast response. Pulsed current operation is often used to produce large torques and very fast response times.

*The small moving coil motor* - In this type of motor the moving coil is housed in between the stationary permanent magnet field, similar to that of a loudspeaker. The moving coil armature is iron-free and hence of low inertia and inductance. This type of motor has a useful range of between 0-10 W.

*The dc torque motor* - Generally used for high torque, stall type operation in position control systems. Brushless dc torque motors employ a constant reluctance magnetic circuit and a precision toroidally distributed armature winding, thus avoiding non-linear effects and torque rippling. When used over a pre-defined range, this type of motor provides high resolution, efficiency, reliability and performs in a linear fashion.

#### 5.2.2.2 Stepper motors

Digital control techniques have meant that this type of motor has found widespread use in the last decade, mainly in the area of computer peripherals. This type of motor can be found in three variations as listed below:

- Permanent Magnet;
- Variable Reluctance, and
- Hybrid - a combination of the first two.

Typical permanent magnet steppers have high step sizes of  $90^\circ+$  and holding torques of 3-20 mNm. Variable reluctance steppers have their place in small sizes, for scientific and light engineering applications, they have step sizes of between  $7.5^\circ$  and  $15^\circ$  with holding torques of up to 300 mNm. Hybrid stepper motors have standard step sizes of  $0.9^\circ$ - $1.8^\circ$ , together with holding torques of up to 7 Nm and are therefore more widely used in the robotics field where high resolution and large torques are required.

The motion of the rotor is in a sequence of steps, the angle of which is determined by the number of stator and rotor teeth. Each stator tooth has a coil wound around it, which is energised by a dc current. When two opposing stator teeth are energised they attract the closest rotor teeth and hence the rotor is moved in a clockwise or anti-clockwise direction (see figure 5.14). The step size can be anywhere from  $0.9^\circ$  up to  $120^\circ$  or more

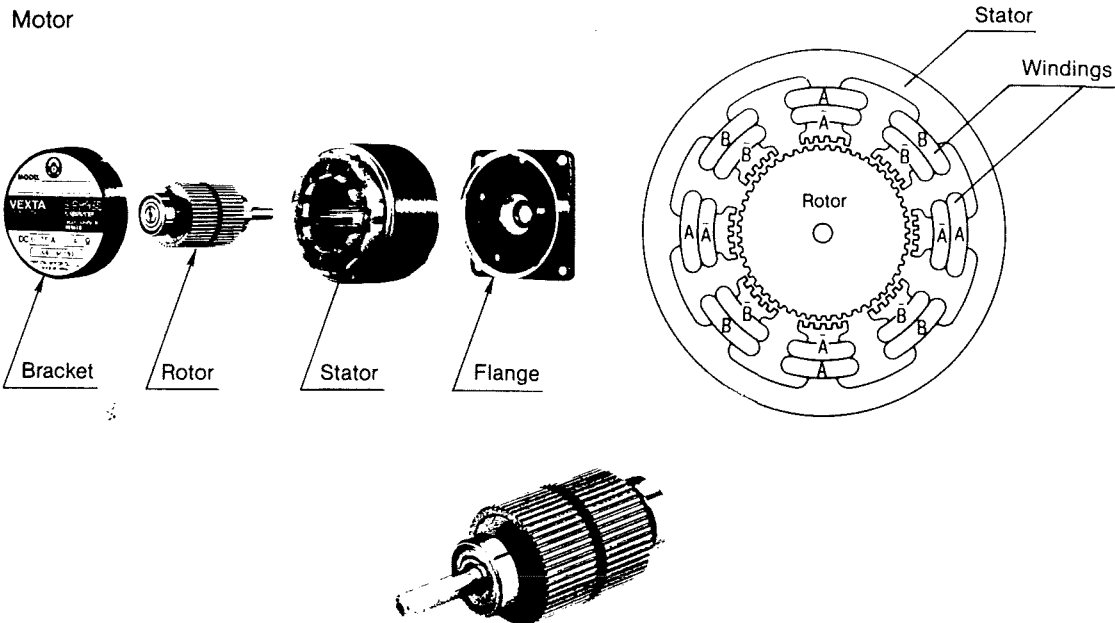


Figure 5.14 - Hybrid stepping motor (Oriental Motor Co Ltd).

depending on the design application. Smaller step sizes are also available with the use of microstepping techniques (200 to 50,000 steps/rev), however, the cost of this is significant. The precision movement of the rotor enables open loop control techniques to be utilised, thus eliminating the need for shaft encoders, resolvers, etc. These motors have the benefits of low-cost, ruggedness, simplicity in construction and high reliability. They provide excellent torque at low speeds, up to 5 times the continuous torque of a brushed motor of the same size, or double the torque of an equivalent brushless motor.

### 5.2.2.3 Rotary solenoids

This type of actuator is usually driven from a 24 V dc or 180 V dc power supply and has a stroke of between 25° to 95°, with single (spring return) or double actuation. Output torques are highest using impulse duty cycles for the 180 V dc version and can range up to 5 Nm, though the torque does vary over the actuator's stroke.

### 5.2.3 Summary

A comparison has been made of the relative performance parameters of a large range of commercially available rotary pneumatic, hydraulic and electrical actuators together with the flexator actuator (see Appendix B1 and B2).

When compared with direct-drive electrical motors the flexator actuator falls in the size category medium to large. With other forms of actuation the flexator has a  $T_p/MM$  ratio

higher than any electrical torque motor and higher than all but the largest vane type pneumatic actuators. However, none of the actuators analysed can compete with hydraulic actuators when operated at 210 bar, in terms of their  $T_p/MM$  ratio. It should be emphasized, that in Appendix B1, the torque values for the conventional pneumatic and hydraulic systems were given in terms of an operating pressure of 6 bar.

The flexator actuator also has the advantage that both its torque and its angular displacement are dependent on the drive shaft diameter and therefore can be varied (within material constraints) to produce any desired operating characteristic. Also, the cost of the flexator actuator is much lower than the majority of actuators.

Pneumatic actuators whether conventional or unconventional have some very useful properties when used as drives for robotic devices. The key to the successful implementation and control of these drives lies in developing simple but effective control algorithms and components, which will enable performance and control of these systems to be on a par with conventional electrical servo motor technology (Mannetje, 1981; Collie, 1992).

### 5.3 THEORETICAL ANALYSIS

A theoretical analysis has been conducted on the flexator system using the Non-Steady Flow Energy Equation (N.S.F.E.E.) to determine:

- A theoretical equation governing the performance of the system;
- The efficiency of the current system, and
- Ways in which the performance can be improved.

The filling of the flexator can be considered to be a non-steady flow process because the rate of mass flow across the boundary of the system varies with time.

Figure 5.15 overleaf, shows the open system for a single flexator. The thermodynamic properties of the fluid at station 1 are assumed to be constant throughout the process, the fluid velocity,  $C_1$  is negligible and the potential energy,  $P.E.$  is zero. The flexator has a variable volume,  $V^i$  when empty and  $V^{ii}$  when filled. The analysis does not account for the elastic strain in the flexator material or any frictional effects in the actuator.

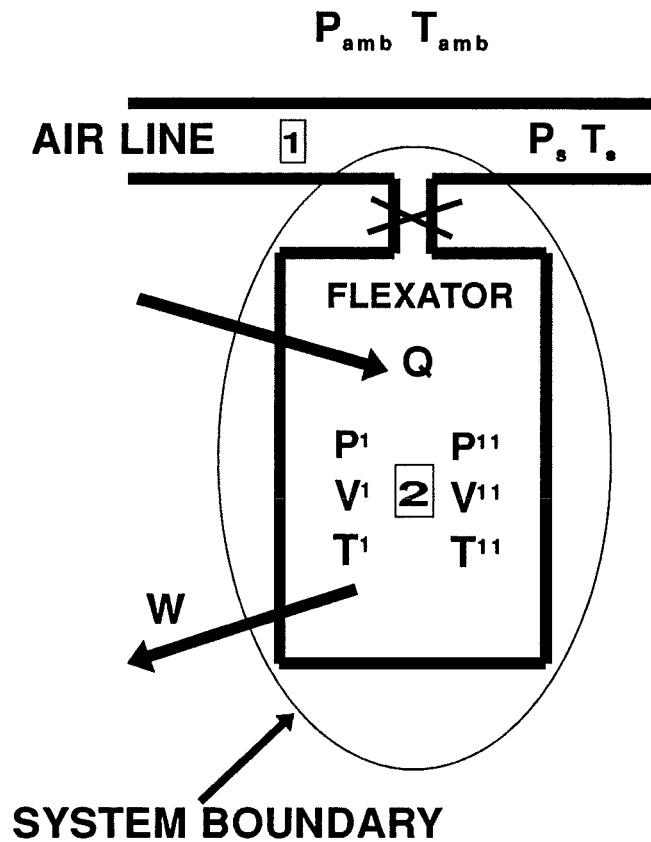


Figure 5.15 - Thermodynamic schematic for a single flexator.

### The Non-Steady Flow Energy Equation

$$Q + \sum \delta m_1 (U + P v + KE + PE) = W + \sum \delta m_2 (U + P v + KE + PE) + \delta m (U + KE + PE), \quad (5.10)$$

Where  $Q$  = Heat Energy Transferred;  $P$  = Absolute Pressure;  $U$  = Internal Energy;  $v$  = Specific Volume;  $KE$  = Kinetic Energy [ $c^2/2$ ];  $PE$  = Potential Energy [ $gz$ ];  $m$  = Mass;  $W$  = Work Done.

Since no fluid leaves the system, the N.S.F.E.E. reduces to:

$$Q + \sum \delta m_1 (U + P v + KE + PE) = W + \delta m (U + KE + PE), \quad (5.11)$$

From thermodynamic relationships:

$$h = U + P v \quad (5.12)$$

Where  $h$  is the specific enthalpy of the air.

Assuming that the process is that of a reversible adiabatic, then  $Q=0$  (ie no heat energy is transferred into or out of the system), and that the kinetic and potential energy terms are zero, therefore:

$$h_1 \sum \delta m_1 = W + (m^{11} u^{11} - m^1 u^1) \quad (5.13)$$

Mass is conserved therefore:

$$h_1 (m^{11} - m^1) = W + (m^{11} u^{11} - m^1 u^1) \quad (5.14)$$

From thermodynamic relationships:

$$h_1 = c_p T_s; U^{11} = c_v T^{11} \text{ \& } U^1 = c_v T^1 \quad (5.15)$$

Where  $c_p$  and  $c_v$  are the specific heats (at constant pressure and constant volume respectively),  $T^1$  and  $T^{11}$  are the absolute temperatures of the air in the flexator at the beginning and end of the process and  $T_s$  is the absolute temperature of the air at station 1 (see figure 5.15).

We therefore have:

$$c_p T_s (m^{11} - m^1) = W + c_v (m^{11} T^{11} - m^1 T^1) \quad (5.16)$$

For a perfect gas:

$$PV = mRT \quad (5.17)$$

Where  $R$  is the specific gas constant, therefore:

$$m^1 = \frac{P^1 V^1}{R T^1} \quad (5.18)$$

$$m^{11} = \frac{P^{11} V^{11}}{R T^{11}} \quad (5.19)$$

The work term  $W$ , can be broken down into two main parts:

- *The work done by the system in moving the load.*
- *The work done in expanding against atmospheric pressure.*

$$W_1 = (M g r \theta_{rad}) \quad (5.20)$$

$$W_2 = P_{am} (V^{11} - V^1) \quad (5.21)$$

$$W = W_1 + W_2 \quad (5.22)$$

Therefore after substituting and rearranging in terms of  $\theta_{rad}$  we have:

$$\theta_{rad} = \frac{\eta}{Mgr} \left( \frac{c_p T_L}{R} \left( \frac{P^{11} V^{11}}{T^{11}} - \frac{P^1 V^1}{T^1} \right) - \frac{c_v}{R} (P^{11} V^{11} - P^1 V^1) - P_{am} (V^{11} - V^1) \right) \quad (5.23)$$

Assuming an isothermal process and initial volume  $V^1$  is zero, the equation becomes:

$$\theta_{rad} = \frac{\eta}{Mgr} [ (P^{11} - P_{am}) V^{11} ] \quad (5.24)$$

$$\theta_{rad} = \frac{\eta}{Mgr} [ P_{gauge}^{11} V^{11} ] \quad (5.25)$$

$$\theta_{rad} = \frac{\eta}{T_L} [ P_{gauge}^{11} V^{11} ] \quad (5.26)$$

Where  $T_L$  is the load torque in Nm.

Equation 5.26 would tend to imply that the angular displacement of the system,  $\theta_{rad}$  would continue to increase linearly as the gauge pressure increased, this is true only up to a value of  $V^{11}$  which is less than the  $V_{max}$  condition (see below). For a given flexator actuator, (fixed diameter of output drive shaft) the maximum angular displacement is determined by the size (volume) of the flexator. Once the maximum volume condition has been reached, increasing the internal pressure can only seek to increase the stiffness of the joint. The flexator actuator can be used to maintain a constant angular position for different torque conditions by increasing or decreasing its internal air pressure.



### 5.3.1 Limiting Conditions & Experimental Results

The N.S.F.E.E. above gives a first estimate of the performance of the flexator actuator and is only valid for values of  $V^{11}$  less than or equal to  $0.8V_{max}$ . Where  $V_{max}$  is the maximum volume of the flexator under no load conditions (see Appendix C). Once the flexator reaches the  $V_{max}$  condition, an increase in pressure will not result in an increase in the angular displacement,  $\theta_{rad}$ .

For more accurate results using the N.S.F.E.E. the governing equation is therefore:

$$\frac{V^{11}}{V_{max}} \leq 0.8 \quad (5.27)$$

Experimental measurements of the independent variables of pressure, volume and angular displacement have shown that the efficiency of the flexator actuator varies with the applied torque load. For the 60 x 90 type flexator actuator, the efficiency varies between 0 and 67%, in a bell shaped distribution (see figure 5.16).

The theoretical analysis of the flexator system is based on the following assumptions:

- Q is zero (adiabatic - no heat energy lost or gained by the system);
- Kinetic and potential energies are zero (no energy of particle motion or by reason of height);
- Mass is conserved (no loss of mass within the system, ie leaks);
- Assuming a perfect gas as the working medium (ie fundamental gas laws apply);

Dual Actuator Type: 60 x 90 ; 5

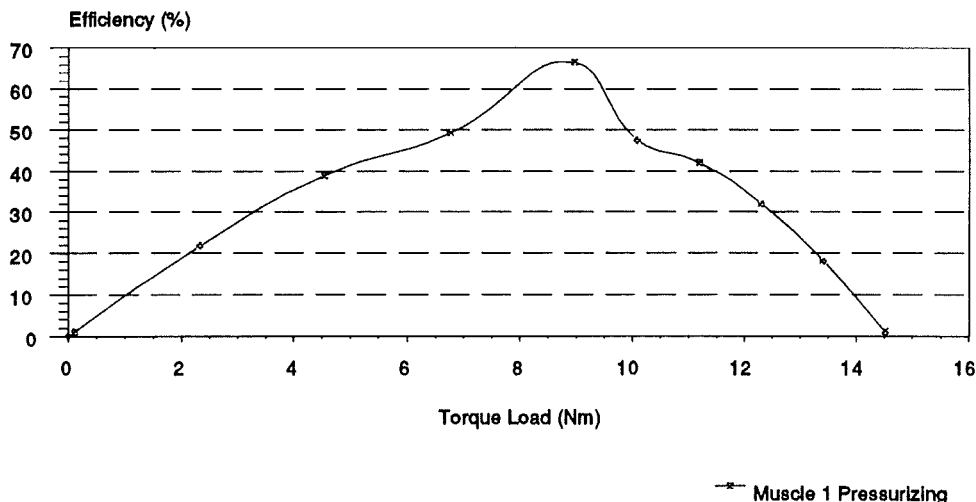


Figure 5.16 - Variation of efficiency with load torque.

- No frictional losses in the system (static and dynamic bearing friction, webbing strap friction and flexator material friction);
- No work is done in stretching the flexator material (strain energy);
- An isothermal process (constant temperature process), and
- Initial volume,  $V^l$  is zero (if it is not then the full equation must be used, Eqn 5.23).

Investigations have been conducted into some of the above areas, such as the amount of heat energy lost or gained by the system, using the non-steady heat transfer equations. Dynamic testing showing the process of filling or emptying to be essentially isothermal, and analysis of the frictional losses in the test-rig (see Appendix D).

If a more comprehensive theoretical analysis were to be performed, to include all the above factors, then the governing N.S.F.E.E. would be much more accurate, but would also be much more complicated and therefore less easy to use.

#### 5.4 SINGLE FLEXATOR PERFORMANCE TESTING & ANALYSIS

The flexator can be used as a linear or rotary actuator. However, from an analysis of both forms, the flexator appears best suited to the rotary configuration. When used as a linear actuator it has a limited stroke and a low power output. The flexator was therefore used in the rotary configuration throughout this investigation.

The static performance tests described here involved testing the flexator in twelve different rotary configurations, by varying its length and width. To enable this, a single-axis test-rig (see Section 5.1.4.1 and Appendix E) was constructed to test single flexators. The test-rig instrumentation, incorporated sensor measurement of:

- Inner drive shaft angular position,  $\theta_{rad}$  ;
- Supply pressure,  $P_{supply}$  ;
- Flexator pressure,  $P^l$  ;
- Flexator air temperature,  $T^l$  ;
- Flexator mass flow rate,  $\dot{m}$  ; and
- Inner drive shaft torque,  $T_q$ .

The flexator actuator was tested in the static sense due to the fact that unlike other more conventional actuators, it does not reach a steady state velocity and therefore cannot be tested using conventional torque-speed analysis curves. Figure 5.17 shows how the sensors were interfaced to a PC-30A/B data acquisition board (Amplicon Ltd) installed in a PC, which was used to store and recall data, plot results, and export data for use in

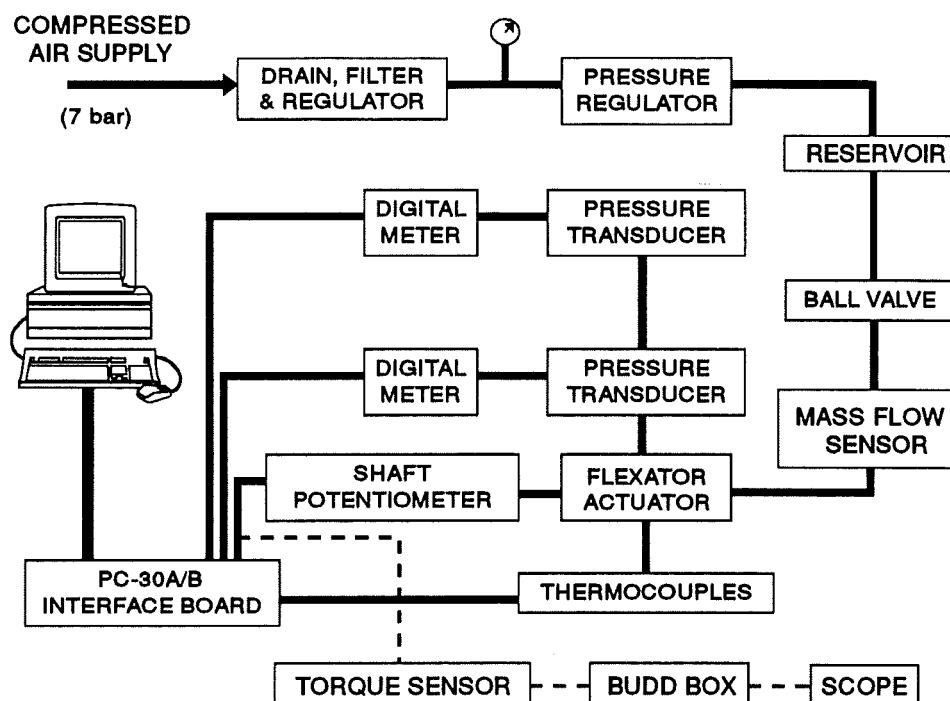


Figure 5.17 - Schematic of test-rig data acquisition system.

other software packages such as Techni-curve and Harvard Graphics. A further test-rig was constructed based on the original design, and was used to test the flexator in the dual muscle antagonistic configuration utilising the same data acquisition system, in order to establish the efficiency of the flexator as well as other performance characteristics.

#### 5.4.1 Single Flexator Test Results

Appendix F1 contains the static test results for the 12 different flexator types tested during this analysis. The results in this section can be categorised into two:

- (I) Graphs of the static performance of the flexator under varying torque load and pressure conditions, and
- (II) Graphs of the flexator spring stiffness coefficient,  $K$  ( $\text{Nm deg}^{-1}$ ).

To test part I, suitable torque loads were chosen such that a range of data could be obtained, within the limits of the test-rig, ie between  $0$ - $300^\circ$  of angular rotation. The tests were conducted by starting at zero flexator gauge pressure and zero angular displacement, and taking readings of the angular displacement at intervals of  $0.5$  bar up to a maximum of  $3.5$  bar gauge (the limit of the original pressure sensors), and then back

to zero gauge pressure. This allowed the level of hysteresis for each type of flexator to be quantified (see Appendix F2).

For the purpose of testing part II above, a set point was chosen, eg 2.5 bar gauge and 8 kg, from which to begin loading the system, the flexator was sealed off from the air supply and readings of the angular displacement and the flexator gauge pressure were taken as the load was increased. The set point for these tests was restricted by the maximum permitted pressure level of the pressure transducer, which was 3.5 bar gauge.

These results show that the flexator pressure increases linearly and the angular displacement decreases linearly with the increasing load torque. Thus the spring stiffness for each flexator type was found. Tests have shown, however, that the spring stiffness changes, depending on the set point chosen for the test. Thus a range of values may be required depending on the operating conditions (see figure F1.6).

#### 5.4.1.1 Hysteresis analysis

From the graphs of the static muscle tests (Appendix F1) it can be seen that the level of hysteresis inherent in the single flexator actuator is a significant factor when used in this configuration. The amount of hysteresis in the system tends to increase as the wrap around length of the flexator increases. There also appears to be a general trend of increased hysteresis with increased torque load,  $T_L$ .

Hysteresis is quantified in terms of the maximum hysteresis, expressed as a percentage of the full scale deflection (f.s.d.) or span of the system.

$$\text{Max Hysteresis} = \frac{\hat{H}}{(O_{\max} - O_{\min})} \times 100 \% \quad (5.28)$$

Where  $\hat{H}$  is the maximum difference between the outward output line and the return line, and where  $O_{\max}$  and  $O_{\min}$  are the maximum output and minimum output values respectively.

The level of maximum hysteresis for these tests varied from 33% to 97% (see Appendix F2). The hysteresis problem has been extensively investigated during the static testing stage to try to understand the main factors which influence it, and to try to develop methods to reduce its magnitude.

There were a number of possible causes of the hysteresis:

- Local regions of high pressure developing in the flexator;

- Frictional effects in the test-rig bearings, the webbing strap and the flexator;
- The inherent non-linearity of pneumatic structures, and
- Creep and elasticity in the webbing strap and flexator materials (see Appendix E).

The first step in investigating this problem involved tapping into the side wall of a flexator under test and measuring the internal flexator pressure, instead of the supply pressure (see figure 5.18). This test showed that the supply pressure and the internal flexator pressure were exactly the same. This showed that there was no localised high pressure region developing in the flexator.

The next step was to try to measure the volume of the flexator for the outward and return strokes. Because there was no suitable flow measurement equipment available at the time, this was achieved by inflating the flexator to the desired pressure, then sealing the inlet pipe and disconnecting it from the main air line. The air in the flexator was then drained into a condom held over the open end of the outlet pipe.

To measure the volume of this air, a container of water was placed onto an electronic weighing scales, pressing the tare button set the scales to zero. The inflated condom was then carefully submerged in the water, the displaced volume of water giving a reading on the scales. The estimated volume of air was therefore the reading in kg divided by the density of water, ie  $1000 \text{ kg/m}^3$ . To estimate the original volume of air the perfect gas equation was used:

$$P^1 V^1 = P^{11} V^{11} \quad (5.29)$$

Assuming that the process of expansion was isothermal.

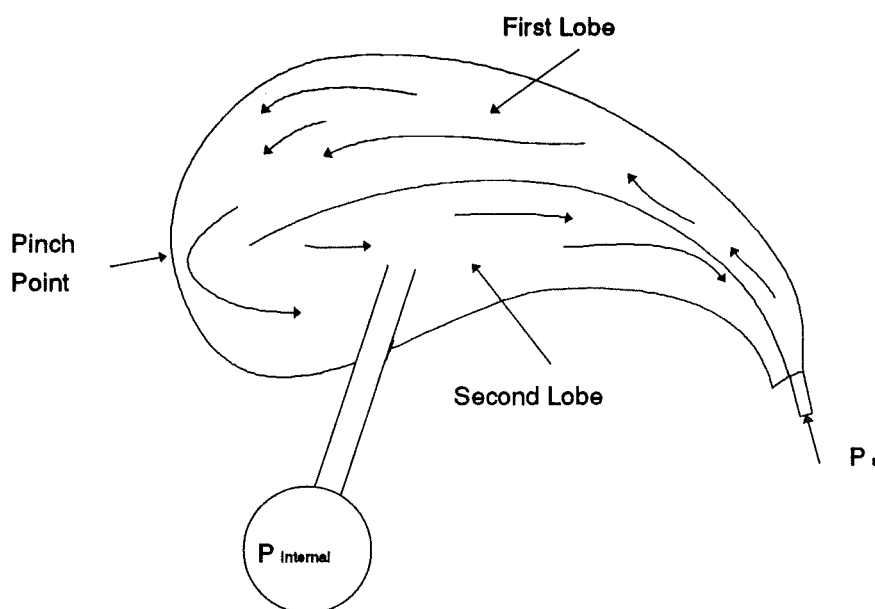


Figure 5.18 - Measurement of flexator internal air pressure.

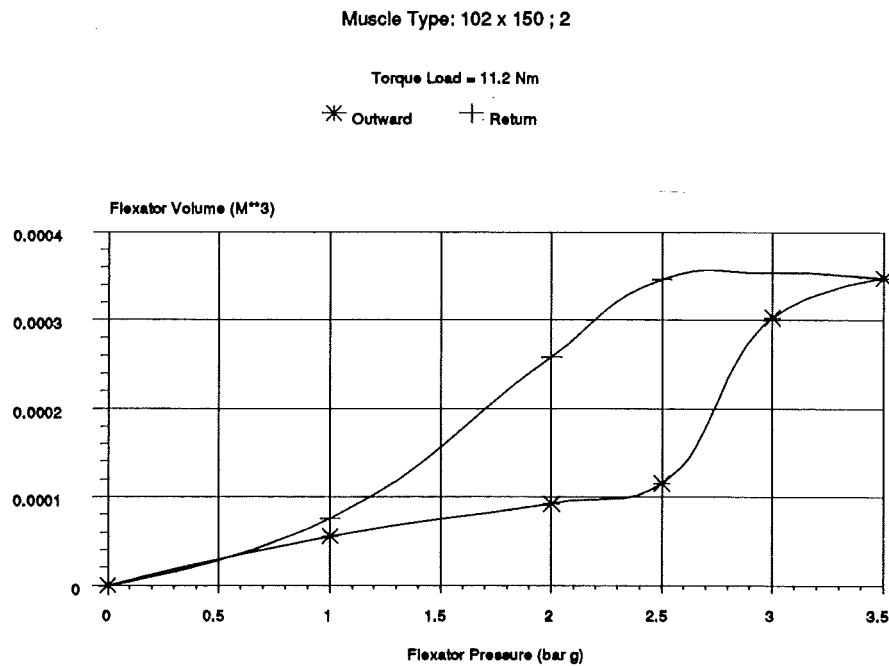


Figure 5.19 - Flexator volumetric test showing hysteresis.

From figure 5.19, it can be seen that the volume of air in the flexator also exhibits hysteresis when the internal pressure is reduced.

The next stage involved investigating the frictional effects within the test-rig bearings. To measure the static friction in the bearings of the test-rig, the flexator together with the webbing strap were removed and a small load was suspended from the steel cable. The torque load was increased until the pulley just began to turn in a clockwise direction. The loading direction was then reversed and the torque load required to just move the pulley in an anti-clockwise direction was then measured.

Table 5.3 - Static Frictional Torque of Test-rig Bearings.

| Shaft rotation direction             | Torque load required to just cause shaft movement. (kg) | Static frictional bearing torque (Nm) |
|--------------------------------------|---|---------------------------------------|
| Clockwise<br>(Muscle Contraction)    | $50 \times 10^{-3} \pm 10 \%$                           | $0.06 \pm 10 \%$                      |
| Anti-clockwise<br>(Muscle Expansion) | $50 \times 10^{-3} \pm 10 \%$                           | $0.06 \pm 10 \%$                      |

The stiction results above would account for some of the hysteresis effects in the smaller flexators operating at low opposing torques, ie the 42 x 90 flexator operating at a torque of 0.67 Nm, where the static frictional effect of the bearings would account for almost

10% of the total opposing torque. However, this would in no way account for the level of hysteresis in the larger flexators, operating at much higher torques.

The frictional losses caused by the webbing strap contacting with the outer tube surface were then investigated. To reduce frictional effects at the point of contact, a PTFE strip was glued to the outer tube window edge; where the webbing strap made contact. Tests were carried out to determine the coefficient of friction,  $\mu$  between the webbing strap and the PTFE strip (see Appendix D). These ranged from approximately 0.15 for the static tests to 0.1 for the dynamic tests. The value of  $\mu$  was found to be considerably higher than that first estimated.

Calculations have shown that the frictional force,  $F$  opposing the motion of the webbing strap can be as high as 150 N, when the angle  $\phi$ , that the webbing strap makes going around the edge of the outer tube reaches  $90^\circ$  (see figure 5.8 and Appendix D).

This is equivalent to 15% of the total torque load, and would account for the increase in the level of hysteresis for the larger flexators, as these have greater strokes. The figure of 15% would increase rapidly as the angle of the webbing strap decreased, reaching a maximum as the angle  $\phi$  approached  $0^\circ$ .

A review of the initial design was undertaken to try to highlight ways in which the frictional effects of the webbing strap could be mitigated. The obvious answer was to prevent the webbing strap touching the outer tube at any point in the operating cycle. A number of different concepts were devised, but since all these involved a complex and expensive redesign of the original system they were not implemented. Other simpler plans were conceived, and these are summarised below:

- Allow the flexator to overhang the window when in its unpressurised state (plan 1).
- Prevent the flexator from moving too far by reducing the drive shaft  $\phi$  (plan 2).
- Modifying the test-rig, joining the webbing strap to a steel cable (plan 3).

The first plan above, only worked with small overhangs, typically less than 20 mm, and only for the 42 mm width flexator, where the width/thickness ratio was low enough to give the flexator some degree of lateral stiffness. The wider flexator tended to become trapped in the window (see figure 5.8) and then would suddenly be released when a critical pressure condition was reached, causing a surge in the angular displacement.

Plan 2, was not implemented during these tests, but should be adopted as a matter of best practice when designing a new actuator system. However, this has the effect of reducing the available torque and thus a compromise solution should be reached.

Muscle Type: 102 x 150 ; 2

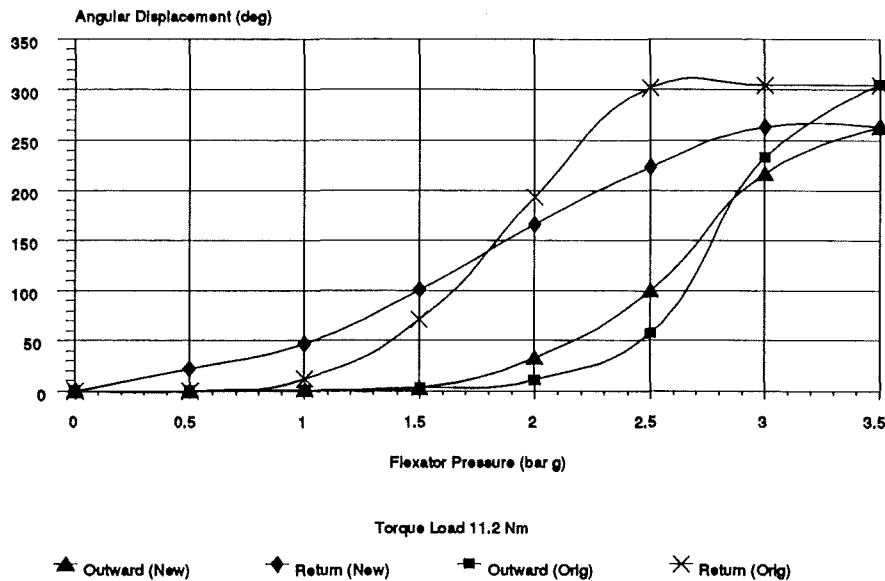


Figure 5.20 - Typical actuator with and without friction.

Plan 3 was adopted as a quick and easy possible solution. This modification consisted of machining four 4 mm wide vertical slots into the outer tube of the test-rig, through an angle of approximately  $90^\circ$  from the edge of the window. Each slot was used for a particular width of flexator. The webbing strap was attached as normal to the outer tube and passed over the outer surface of the flexator to be tested, at the end of the flexator it was joined by a connecting bar to a steel cable of 2 mm diameter which passed through the machined slot and was attached to the drive shaft as normal. As the flexator expanded, the cable passed through the slot, so eliminating frictional contact forces.

The system worked well in removing the frictional forces, however, the bar tended to crush the flexator so changing its shape, the steel cable caused frictional problems on the surface of the flexator and also started to cut into the outer jacket. The system also became unstable when inflating, tending to twist if the webbing strap was not exactly centralised on the flexator. Because of these reasons, the overall system performance in terms of angular displacement was worse than that of the original system, but the maximum hysteresis was reduced from 80% to 60% as can be seen from figure 5.20.

#### 5.4.1.2 Flexator air temperature analysis (see Appendix G)

The theoretical analysis of the flexator (see Section 5.3) assumed that its internal air temperature remained constant (isothermal process) throughout the filling/exhaust cycle. To analyse this in more depth, type k PTFE insulated thermocouples were used together with a purpose-built thermocouple amplifier circuit to measure the air temperature inside a range of flexators during tests with varying torque loads. This type of thermocouple



had an output of 4.0 mV per 100°C temperature change. The maximum voltage gain available from the thermocouple amplifier supplied by the manufacturers was in the order of 250. Due to the small air temperature fluctuations found during initial testing ( $\pm 6^\circ\text{C}$ ), the output voltage swing was found to be too small to measure accurately and therefore required further amplification by a factor of 33 to match the required input characteristics of the PC30A/B data acquisition system (0-10V).

By careful calibration the data acquisition system could read the flexator air temperature from 0 to 30 °C. The calibration error for the amplifier was stated to be  $\pm 3^\circ\text{C}$ . The data files were saved within the PC30's 'Microscope' software package as ASCII files before being imported to Harvard Graphics where data manipulation and calibration took place.

Appendix G shows the results obtained from the tests. From the figures showing flexator air temperature change against time, it can be seen that inflating the flexator causes an increase in the internal air temperature and exhausting the flexator causes a decrease in the internal air temperature. The level of increase or decrease in the flexator air temperature is a function of the maximum flexator volume,  $V_{max}$ , the opposed torque load,  $T_L$ , and the supply pressure,  $P_{supply}$ . The temperature change increases with increased flexator volume and increased supply pressure, and decreases with increased torque load.

Since the flexator would rarely be used under no load conditions, ie  $T_L=0$ , the temperature change would be limited to a few degrees at most. Also, the cycle of inflation and exhaust would tend to keep the air temperature at around the median position. The graphs also clearly show the long period of time taken for the flexator's air temperature to return to their original values. This demonstrates the insulating effect that the synthetic rubber lining has on the air temperature. Further work should investigate the effect of air temperature build-up with large multiple flexator systems operating under light load torque conditions with repeated cycles.

#### 5.4.1.3 Time delay and supply line pressure drop (see Appendix H)

When a flexator at approximately zero volume and atmospheric pressure is suddenly connected to a pressure source at 6 bar gauge, there is a sudden flow of mass into the empty chamber. Due to the small bore size ( $\phi 2.5$  mm) of the supply line (ie low capacity), this high initial mass flow rate causes a sudden drop in supply line pressure, which can amount to an instantaneous pressure drop of 60% when using a large sized flexator with low torque load. It can clearly be seen how the system variables of supply pressure,  $P_{supply}$ , final flexator volume,  $V^f$  and the torque load,  $T_L$  affect the angular displacement,  $\theta_{deg}$  of the flexator actuator.

Figures H.1 and H.3, show the level of pressure drop in the supply line when the inlet valve is suddenly opened. This has the effect of causing a lag or time delay between the step input and the system output. In figure H.3 this amounts to approximately 0.8 sec of time delay and is a significant factor in terms of the control of a flexator joint.

This clearly shows the need for an accumulator of sufficient capacity to match the required volume of the flexator system. By placing the accumulator as close to the actuator as possible, it should be possible to reduce the pressure drop and hence decrease the time delay and increase the angular velocity of the output. It is also possible to graphically see the frictional effect of the webbing strap at high angular displacements, by observing the angular displacement output line (see figure H.3). As the webbing strap begins to touch the edge of the outer tube the output line changes from linear to non-linear.

In summary, from the viewpoint of hysteresis, it is desirable to remove as much of the frictional effects as possible, provided that the method used does not distort the original operation of the flexator. From the tests involving the flexator thermocouples it has been shown that the flexator's filling and exhaust process is essentially isothermal, thus justifying the assumption made in the theoretical analysis.

By careful design of the actuator, and in light of the findings of this section, the designer should attempt to reduce the amount of flexator movement as much as possible by reducing the diameter of the inner drive shaft, using quality bearings of low coulomb friction and making use of PTFE strips or a roller at the edge of the outer tube.

In order to attain maximum operating speed, a flexator actuator should have pressure supply lines of sufficiently large bore size. To reduce supply line pressure drops, accumulators of sufficiently large capacity should be used as a buffer between the supply line and the flexators. These should be placed as close to the actuators as possible, in order to reduce time delays in the supply piping.

However good the design, pneumatic systems will always be non-linear and this type of rotary actuator will always exhibit hysteresis. Since bi-directional control is required in most robotic joints, the next section investigates the use of dual flexator actuators operated in the antagonistic configuration.

## 5.5 INVESTIGATIONS INTO ANTAGONISTIC FLEXATOR PAIRS

A representative size of flexator (60 x 90 mm) was chosen as the actuator to be used to conduct all the dual flexator tests. The reasons for choosing this size of flexator were mainly due to its lower hysteresis values, reduced frictional effects (due to its small length) and adequate torque range (1-6 Nm @ 3.5 bar g). The dual flexator testing phase was conducted using an extended version of the original single flexator test-rig (see Appendix D), together with the original data acquisition system.

### 5.5.1 Description of the Dual Flexator Actuator

The principle of operation of the dual flexator actuator is the same as that for the single flexator actuator. The addition of the second flexator (which opposes the motion of the first) allows for double-acting control of the joint, and by adjusting the length of the webbing straps, the stroke of the actuator can be set to any desired angle, within the range of the particular flexator used (see figure 5.21).

### 5.5.2 Testing the Theory of Controllable Compliance

The theory of controllable compliance was discussed in Section 5.1.2 and an idealised graph was produced to show this phenomena. This section presents the results of tests conducted on the 60 x 90 dual flexator actuator to show whether this theorem is valid for the flexator actuator operating in tandem. The dual flexator test-rig was set-up with two identical 60 x 90 flexators, one opposing the other. A mass was suspended from the

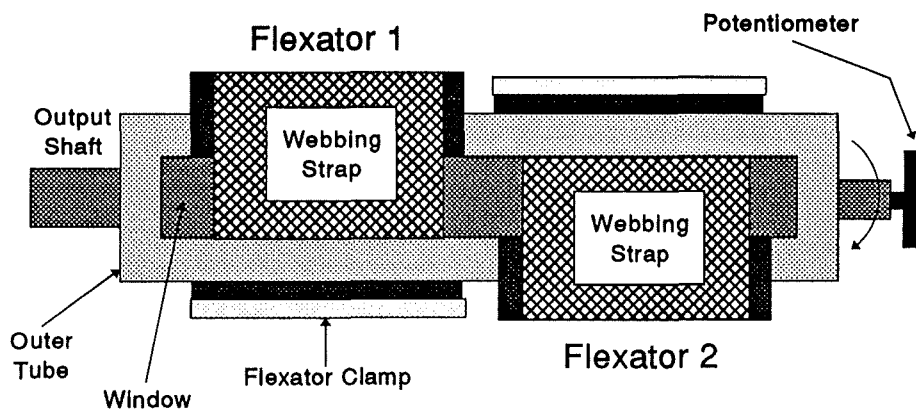


Figure 5.21 - Schematic of dual flexator rotary actuator.

pulley via a steel cable, this produced a constant load torque acting against the second flexator. The supply pressure was split into two lines feeding each flexator via a manually controlled pressure regulator and a pressure transducer (0-6 bar). The pressure in both flexators could therefore be independently and manually adjusted from 0 to 6 bar gauge. Measurement of the dual flexator stiffness was conducted at all pressure ratios between 0 and 6 bar gauge (in 1 bar steps) and for five torque loads between 1.2 and 6.7 Nm. Graphs of torque load against angular displacement were plotted and are shown together with data tables in Appendix J. Due to the large amount of data acquired from these tests, it was decided to plot a graph of the dual flexator stiffness against angular displacement of the joint, for the 3.436 Nm load case only (see figure 5.22).

From figure 5.22 we can observe the inherent non-linear properties of the flexator actuator. Each point on the graph represents a unique pressure ratio between the two flexators and hence a specific angular position and stiffness. The theorem states that by increasing the pressure in a pair of antagonistic pneumatic muscles whilst maintaining the pressure ratio, the angular position of the joint is kept constant, but its stiffness increases. The graph although crude in the sense that the readings were taken at one bar intervals, does show that the stiffness of the joint can be increased whilst maintaining the angular position by increasing the pressure in the two flexators, eg from [1-3] to [2-6]. Due to the fact that one flexator has all of the load torque acting against it, the graph is non-symmetrical about the zero angular displacement line.

The system is therefore non-linear (under normal operation), non-symmetrical (due to the load torque) and its stiffness is modulated by the pressure ratio between the two flexators, their size and the level of load torque opposing the motion.

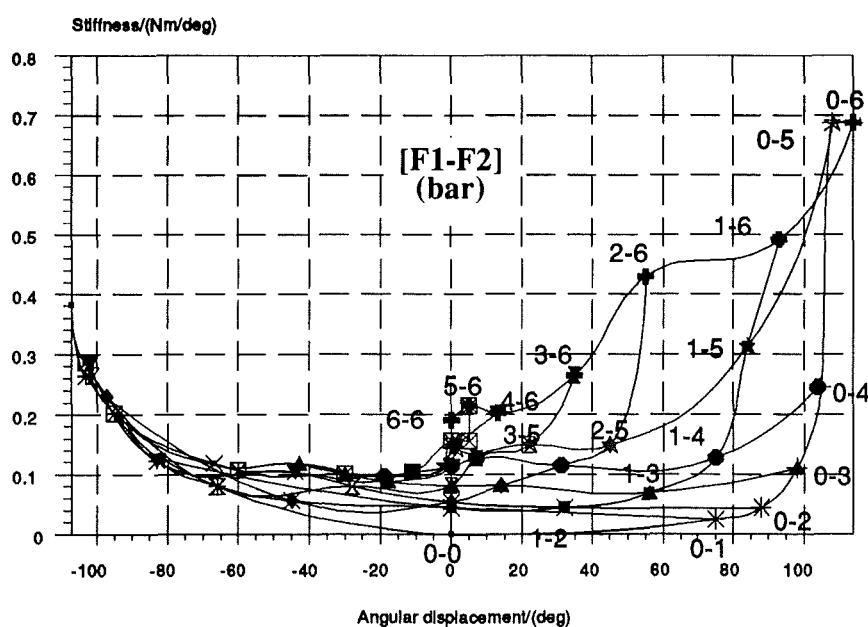
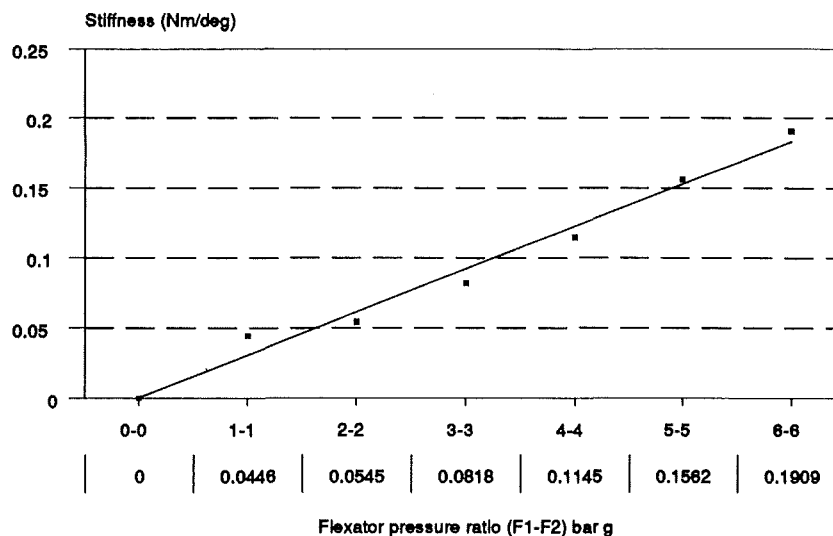


Figure 5.22 - Controllable compliance of the dual flexator.



Stiffness measured @ 3.436 Nm torque load  
Torque load opposing flexator 2

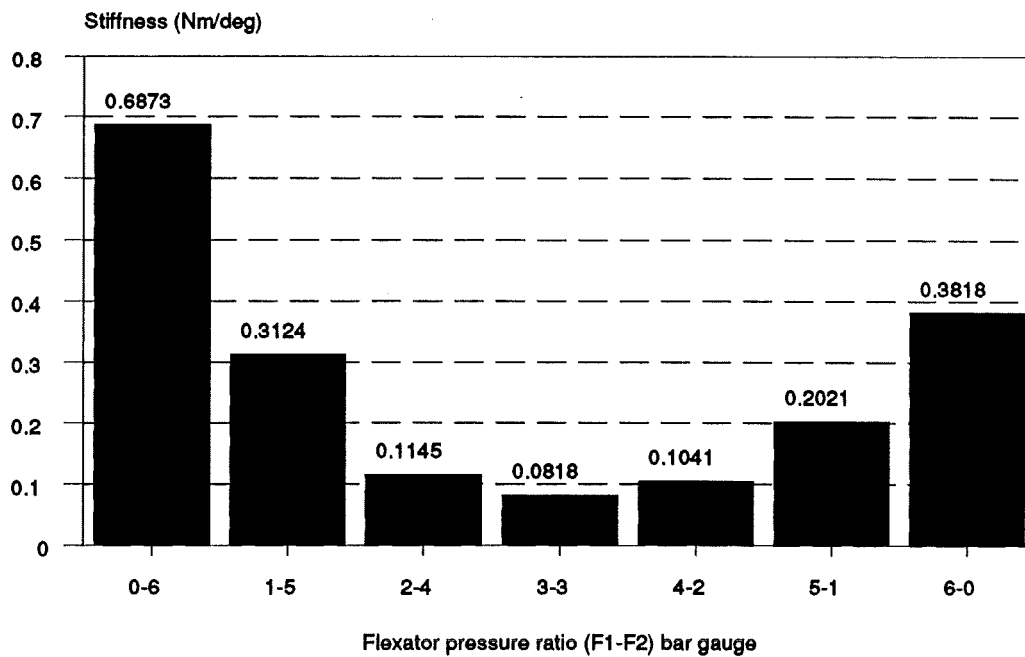
Figure 5.23 - Linear stiffness with constant pressure ratio.

Figure 5.23 shows that the stiffness of the joint increases linearly (as expected) when both flexators have their pressure increased linearly from 0 to 6 bar gauge in one bar intervals. If an infinite pressure source was available, then it would be possible to infinitely modulate the stiffness of the joint; this of course is an idealised situation.

Figure 5.24 shows how the stiffness of the system is modulated by cycling the dual flexator actuator from [0-6] bar through to [6-0] bar in one bar intervals. The stiffness of the joint is lowest when both flexators are at the same pressure, ie 3 bar and increases as the pressure ratio increases either side. The highest stiffness values as expected occur at the end of stroke positions where one flexator is fully charged and the other is fully vented. The [0-6] bar configuration has a higher stiffness than the [6-0] configuration due to the fact that the second flexator (which is at 6 bar) is preventing any movement of the first flexator (which is at zero bar and fully vented). Thus, the stiffness is much higher than the opposite condition.

### 5.5.3 Testing the Dynamic Performance of the Dual Flexator Actuator

The use of manually operated pressure regulators in the above tests meant that although accurate pressures could be set, this process was time consuming and the results were static, ie for each specific pressure ratio and load case the actuator stiffness was measured. Under normal operating conditions the dual flexator actuator would be cycled between its end states, ie one flexator almost fully charged and the other flexator almost fully vented and vice versa.



Stiffness measured @ 3.436 Nm torque load  
Torque load opposing flexator 2

Figure 5.24 - Dual flexator cycling stiffness.

A series of dynamic tests with varying torques loads (ten load cases) was therefore conducted on the 60 x 90 dual flexator actuator using the data acquisition system to record the variables of flexator pressures, angular displacement and volumetric flow rate. The data obtained, was imported into a Lotus spreadsheet before being processed to give the standard units of absolute pressure ( $\text{N/m}^2$ ), flexator volume ( $\text{m}^3$ ), power in and power out (Watts). Once these calculations were performed for each time step, graphs were produced to show the dynamic performance of the dual flexator actuator. These graphs consisted of  $P$ - $V$  diagrams, graphs of flexator pressures and flow rates, and angular displacement against time. It was also possible to plot other variables such as angular velocity, input and output power, and efficiency against time for each torque load case. The graph of actuator efficiency against torque load has already been shown (see figure 5.16).

#### 5.5.3.1 The dual flexator pressure-volume diagram

The pressure-volume  $P$ - $V$  diagram for a pneumatic system gives the thermodynamicist an indication of the type of process taking place. When a gas undergoes a reversible process in which heat is transferred, the process frequently takes place such that a plot of  $\log P$  versus  $\log V$  gives a straight line. For such a process  $PV^n = \text{constant}$ . The value of the exponent  $n$  depends on the type of process. The value of  $n$  for some common processes are given below:

- *Isobaric process (constant pressure)  $n=0$*
- *Isothermal process (constant temperature)  $n=1$*
- *Isentropic process (constant entropy)  $n=k$*
- *Isometric process (constant volume)  $n=\infty$*

There are an infinite number of processes that follow the  $PV^n=C$  law, with  $n$  ranging from plus to minus infinity. These are known as polytropic processes. As mentioned previously,  $P$ - $V$  diagrams for the dual flexator actuator moving through a typical working cycle were plotted for different torque loads and the values of  $n$  were calculated. A representative example of a typical  $P$ - $V$  diagram is shown in figure 5.25. It can be seen that the charging of the dual flexator actuator can be described as a three phase polytropic process which encompasses a region of constant pressure, ie  $n = 0$ . The area under the  $P$ - $V$  curve represents the work done by the system.

### 5.5.3.2 Measurement of the dynamic control variables

As previously stated the main control variables of flexator pressures, volumetric flow rates and angular displacement were measured directly via the test-rig sensors and the data acquisition system. The raw data in terms of analogue voltages was then imported into a Lotus spreadsheet and the secondary variables were calculated.

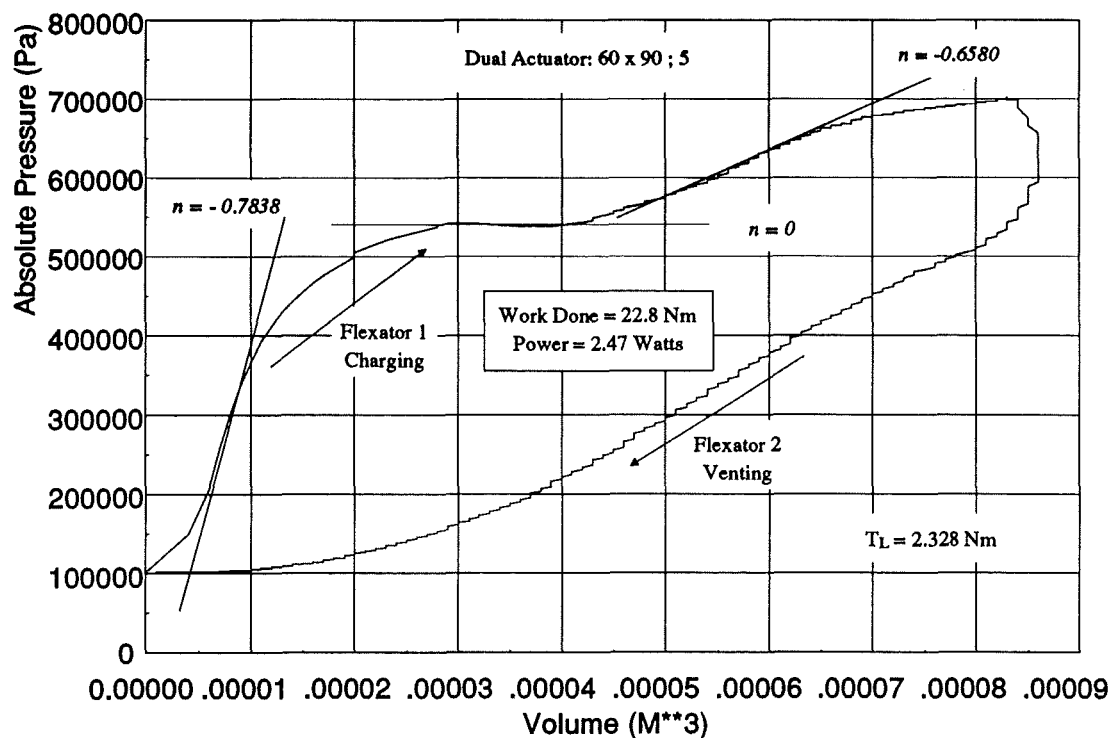


Figure 5.25 - PV diagram for the dual flexator actuator.

Figure 5.26 below plots the main control variables (as voltages) against time for the 60 x 90 dual flexator actuator, with a very light torque load of 0.1 Nm. As a comparison a similar plot is shown in figure 5.27 for the same actuator with a torque load of 11.2 Nm.

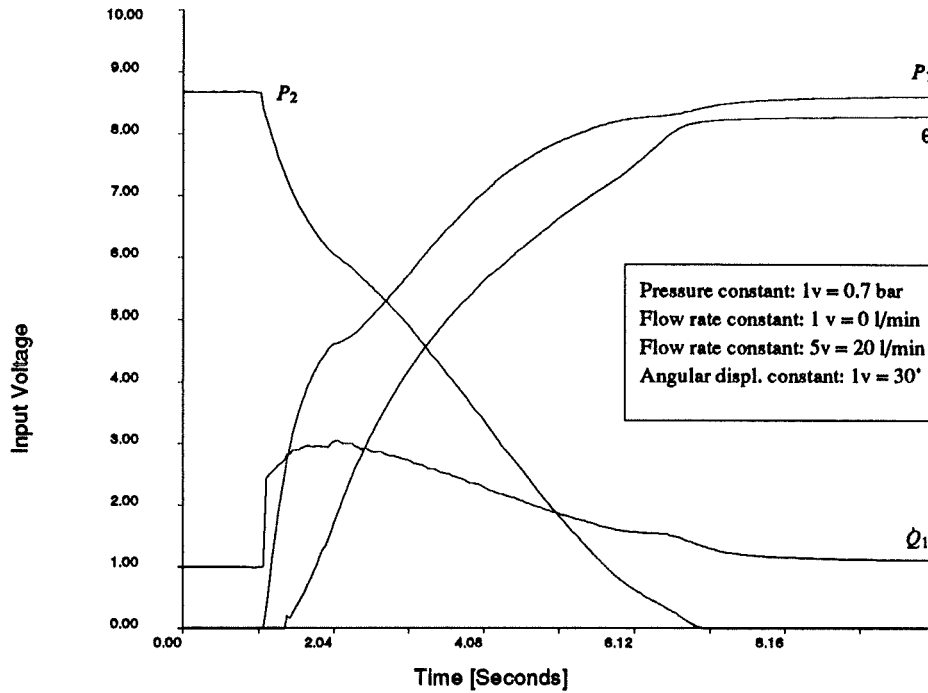


Figure 5.26 - Dynamic measurement of variables @ TL=0.1 Nm

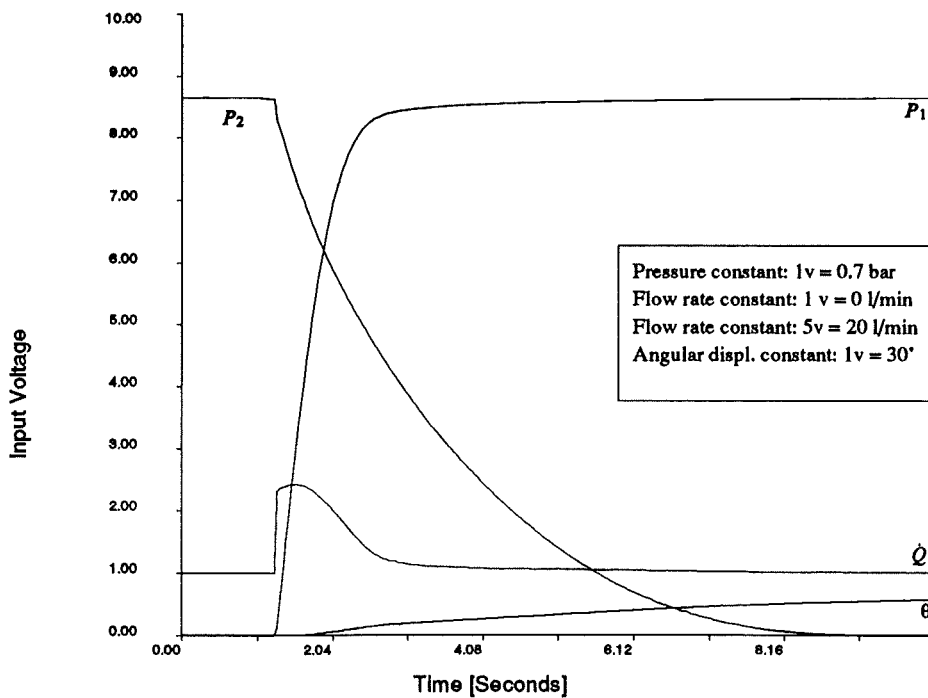


Figure 5.27 - Dynamic measurement of variables @ TL=11.2 Nm



## 5.6 SIMULATION OF THE DUAL FLEXATOR ROTARY ACTUATOR USING ACSL

A 60 x 90 dual flexator actuator was simulated using the advanced continuous simulation language (ACSL) on a VAX 8530 mainframe computer. The simulation program was firstly used to obtain values for the dynamic and static friction terms by matching the performance of the system with data from experimental testing. Once the simulation was validated it was then used to predict the performance of the actuator, whilst varying the system constants such as the system inertia, torque load, etc. From this analysis the operating characteristics of this size of actuator was predicted. The simulation program was designed to be highly flexible so that any of the control variables or system constants could be changed during run-time, thus producing an interactive analysis program. Any size of dual flexator actuator could be simulated using this program, provided that the initial conditions and actuator constants are known.

### 5.6.1 Description of the Physical System

The dual flexator system can be described as a double-acting rotary pneumatic actuator. The simulation of the dual flexator actuator assumes that the system can be modelled by a vane type rotary actuator with two chambers separated by a single vane with hard stops at the end of stroke positions. Each chamber has an input/output port which is connected to the inlet/exhaust solenoid valves and manifold block as described in Section 7.5 (see figure 7.10). The motion of the actuator is governed by the system dynamics, with the speed of operation dictated by the mass flow rate equations, which

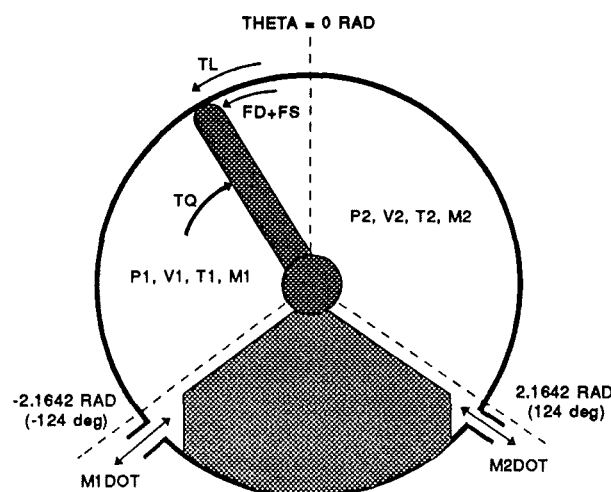


Figure 5.28 - The dual flexator actuator modelled as a vane type actuator.

are in turn a function of the chamber pressures. These equations are given in Section 7.6.2. The fluid medium is air and it is assumed that the perfect gas equations are valid for the limited pressure region over which the system is operating, ie between 1 and 7 bar absolute.

### 5.6.2 Equations of Motion of the Actuator

The output torque of the actuator is a function of the dual flexator torque, viscous frictional torque,  $F_{Viscous}$ , static frictional torque,  $F_{Static}$  which is a function of the angular position and the load torque,  $T_{Load}$ .

$$T_q = ( \lambda - F_{Viscous} - F_{Static} - T_{Load} ) \quad (5.30)$$

Where  $\lambda$  is the torque function of the flexator pair and is based on the actuator design variables (see Section 5.6.7).

From theory:

$$\ddot{\theta} = \frac{T_q}{J_m} \quad (5.31)$$

Where  $\ddot{\theta}$  is the angular acceleration ( $\text{rad sec}^{-2}$ ) and  $J_m$  is the system inertia ( $\text{kg m}^2$ ).

### 5.6.3 Controller Design

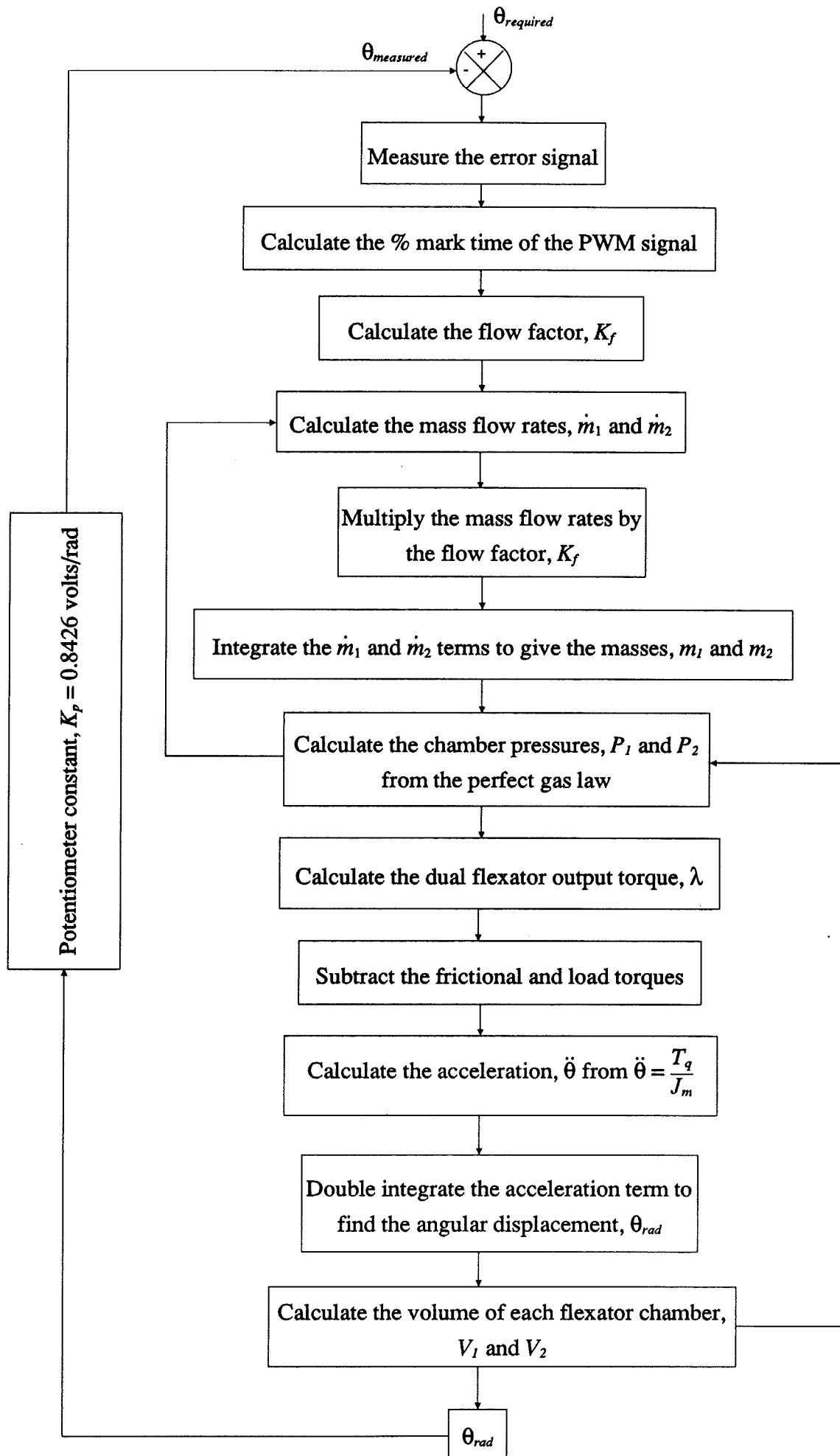
The controller design implemented in the simulation program was an enhanced version of that used in the initial prototypes and consists of a simple proportional error based controller which varies the mass flow rate in proportion to the error signal.

$$\theta_{required} = KT \cdot STEP(TZ) \quad [\text{Step input function in volts}] \quad (5.32)$$

$$\theta_{measured} = KP \cdot \theta \quad [\text{volts}] \quad (5.33)$$

$$Error = (\theta_{required} - \theta_{measured}) \quad [\text{volts}] \quad (5.34)$$

A block diagram of the control system for a single joint is shown overleaf. Once the system has been modelled, more advanced control techniques can be implemented, should this prove necessary.



### 5.6.4 Experimental Data on the 60 x 90 Dual Flexator Actuator

Tests were conducted on this size of dual flexator actuator to measure its performance for increasing torque loads (see Section 5.5.3). In order to accurately simulate the actuator's performance, a relationship between the volume of the flexator and the angular displacement of the actuator was necessary. The instantaneous volume of the flexator was therefore plotted against the angular position of the inner drive shaft, for each torque load (see figure 5.29). Using a straight line approximation for all the measured data it was possible to find an equation relating volume to angular displacement (rad) for both chambers.

$$V_1 = (0.0308E-05 \cdot \left( \frac{(\theta_{rad} + 2.1642)}{\pi} \cdot 180 \right)) + 1.6653E-05 \quad (5.35)$$

$$V_2 = (0.0308E-05 \cdot \left( \frac{(2.1642 - \theta_{rad})}{\pi} \cdot 180 \right)) + 1.6653E-05 \quad (5.36)$$

From the perfect gas equation, the initial mass of gas in each chamber is a function of the initial pressure, initial volume and temperature (assuming an isothermal process).

$$M_{i,INIT} = \left( \frac{P_{i,INIT} \cdot V_{i,INIT}}{R \cdot T_1} \right) \quad (5.37)$$

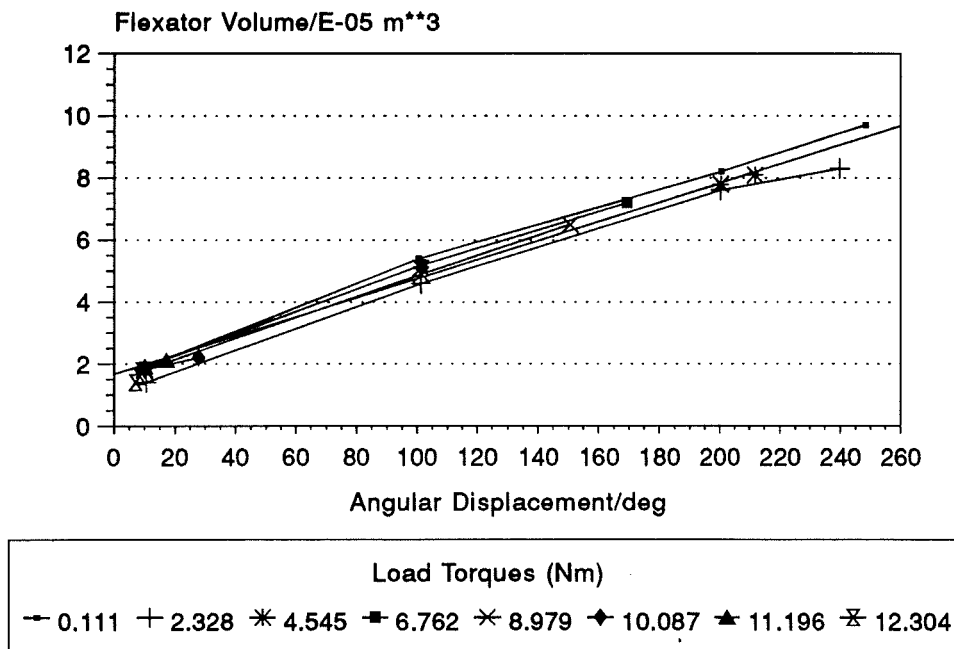


Figure 5.29 - Graph of flexator volume against angular displacement.

$$M_2INIT = \left( \frac{P_2INIT \cdot V_2INIT}{R \cdot T_2} \right) \quad (5.38)$$

The values for the initial mass of gas in each of the two chambers was used when integrating the  $M_1DOT$  and  $M_2DOT$  terms to calculate the loss or gain of mass, and hence the effect that this had on the chamber pressures.

$$M_1 = \int_{t=0}^n M_1DOT + M_1INIT \quad (5.39)$$

$$M_2 = \int_{t=0}^n M_2DOT + M_2INIT \quad (5.40)$$

From equations 5.39 & 5.40 the values of the chamber pressures  $P_1$  and  $P_2$  are found.

$$P_1 = \frac{M_1 R T_1}{V_1} \quad (5.41)$$

$$P_2 = \frac{M_2 R T_2}{V_2} \quad (5.42)$$

### 5.6.5 Proportional Flow Calculation

As described in Section 7.8.2, when using the VJ114 type solenoid valve it was possible to vary the flow rate proportionally by varying the PWM signal's % mark time,  $MT$  (the period of time that the valve is open, see figure 7.19) between 10% and 90%. This method was therefore used in the simulation to calculate a flow factor,  $KF$  which was then used to limit the mass flow rate terms for chambers 1 & 2 between 24% and 100%, based on the magnitude of the error signal. Thus proportional error control was obtained. A more sophisticated non-linear function for the flow factor,  $KF$  could be implemented in the simulation program at a later date, should this prove necessary.

$$KF = \left( \frac{(0.9372 \cdot MT) + 14.801}{100} \right) \quad (5.43)$$

### 5.6.6 Determination of the Static and Viscous Friction Constants

Static friction (stiction) is the force required to initiate relative motion when the surfaces are at rest. Surfaces at rest tend to stick and the force required to initiate motion is greater than the force required to maintain motion. The running friction or coulomb

friction has a constant amplitude and its sign is dependent on the direction of the velocity. The viscous friction consists of a force which is proportional to the relative velocity between the surfaces.

The static and viscous friction terms consist of those associated with the test-rig and those associated with the flexator actuator and webbing strap. The level of frictional torque attributed to the flexator and webbing strap is very difficult to measure accurately, since these quantities vary with the differential pressure and the angular displacement.

The static frictional bearing torque of the test-rig was measured as  $0.06 \text{ Nm} \pm 10\%$  as described in Section 5.4.1.1 (see Table 5.3).

The viscous friction of the test-rig was measured using the logarithmic decrement method. Using this method a spring was attached from one end to the steel cable on the test-rig pulley, and to ground at the other end. A single flexator pressurized to 1 bar gauge, supported the weight of the spring and also enabled it to be tensioned. The pulley was then manually displaced and released. The damping of the angular displacement was recorded using the attached data acquisition system. From theory:

$$\frac{x_1}{x_0} = e^{\left(\frac{-2\pi\zeta}{\sqrt{1-\zeta^2}}\right)} \quad (5.44)$$

The logarithmic decrement,  $\Delta$  is the natural logarithm of the ratio of the amplitudes of two successive cycles of the damped free vibration:

$$\frac{x_1}{x_0} = e^{-\Delta} \quad (5.45)$$

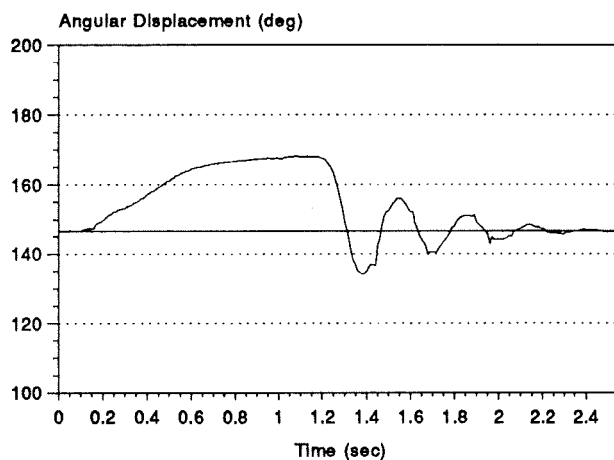


Figure 5.30 - Measurement of the test-rig viscous friction coefficient.

$$\Delta = \frac{2 \pi \zeta}{\sqrt{1 - \zeta^2}} \quad (5.46)$$

From figure 5.30, the values of  $x_1$  and  $x_0$  are 21.53 and 9.52, therefore:

$$\Delta = 0.816 \text{ and } \zeta \text{ (damping ratio)} = 0.13 \text{ (underdamped)} \quad (5.47)$$

From control theory:

$$\ddot{\theta} + \frac{B}{J_m} \dot{\theta} + \frac{K_\theta}{J_m} \theta = 0 \quad (5.48)$$

$$\ddot{\theta} + 2 \zeta \omega_n \dot{\theta} + \omega_n^2 \theta = 0 \quad (5.49)$$

If  $K = 152.4 \text{ N/m}$ ,  $r_p = 0.113 \text{ m}$  and  $J_m = 7.611\text{E-}03 \text{ kg m}^2$ , then the natural frequency is:

$$\omega_n = \sqrt{\frac{K r_p^2}{J_m}} = 15.99 \text{ (rad/sec)} \quad (5.50)$$

Therefore the viscous frictional torque constant for the test-rig is:

$$B = 2 \zeta \omega_n J_m = 0.0316 \text{ (Nm Sec/rad)} \quad (5.51)$$

The static and viscous frictional torque constants for the test-rig have been calculated. Since the test-rig bearings are of high manufacturing quality these constants are, as expected, very low.

However, the static and viscous frictional torque terms for the flexator and webbing strap combination were impossible to measure directly and were therefore obtained by matching the simulation results with the experimental data (see Section 5.6.8).

### 5.6.7 Flexator Theoretical Torque Analysis

A theoretical analysis of the flexator actuator using the non-steady flow energy equation was presented in Section 5.3. This analysis gave a simple equation relating the angular displacement,  $\theta$  in terms of the internal flexator gauge pressure, flexator volume, load torque and efficiency. Since the efficiency of the flexator varies with the load torque and flexator size, a more accurate and generalised torque equation was required for use in the ACSL simulation program.

Recent work by Tillett (1993) has produced a generalised theoretical torque equation for the rotary flexator actuator in terms of its basic design parameters and this is presented in the following section.

#### 5.6.7.1 Torque analysis of the flexator actuator

The torque produced by the dual flexator actuator,  $\lambda$  is equal to the difference between the product of the webbing strap tensions,  $F_1$  and  $F_2$  and the inner drive shaft radius,  $r$ .

$$\lambda = (F_1 \cdot r) - (F_2 \cdot r) \quad (5.52)$$

$$\lambda = (F_1 - F_2) \cdot r \quad (5.53)$$

The inner drive shaft radius,  $r$  is constant, but the tension in the webbing strap decreases with the amount of flexator inflation. The reason for this lies in the reduction in contact area between the flexator and the outer tube as it is inflated. As the flexator is pressurised it tries to straighten and form a circular cross-section, however, because it is folded in two and also constrained by the webbing strap, this will not occur. The resulting form, takes the shape of an elliptical cross-section. The reduction in contact area is therefore both along its radial length and cross-sectional width. Tillett states that over a limited stroke, the angle of the webbing strap between the flexator and deflection roller remains substantially parallel to the axis of symmetry, ie vertical as shown in figure 5.31, this simplifies the analysis.

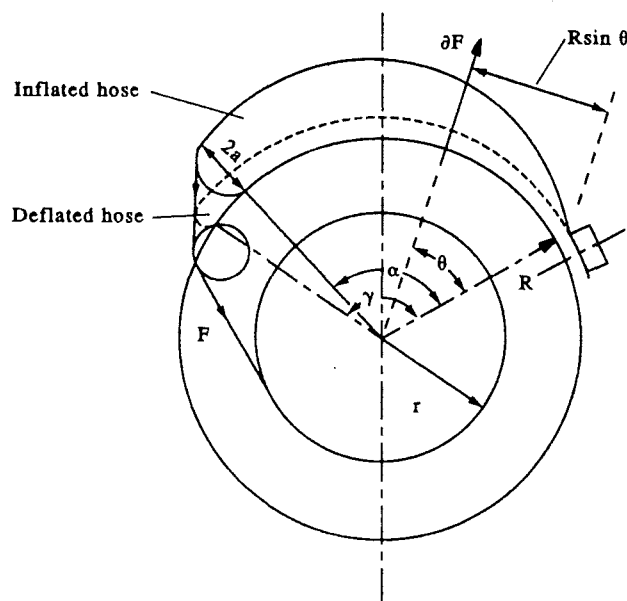


Figure 5.31 - Model of a single flexator rotary actuator (Tillett, 1993).



By considering the flexator and webbing strap as a free body and taking moments,  $M$  about the clamp:

$$M = F 2 R \cos \left( \frac{\pi - \gamma}{2} \right) = \int_0^\alpha R \sin \theta \partial f \quad (5.54)$$

$$\partial f = P W R \partial \theta \quad (5.55)$$

Where:

$\partial f$  = elemental reaction force between the flexator and the outer tube (N);

$F$  = webbing strap tension (N);

$P$  = flexator internal air pressure ( $N/m^2$ )(gauge);

$R$  = outer tube radius (m);

$r$  = inner drive shaft radius (m);

$W$  = cross-sectional contact width of the flexator (m);

$\theta$  = angle between the clamp and an elemental reaction force (rad);

$\alpha$  = angle between the clamp and the flexator breakaway point (rad), and

$\gamma$  = wrap around angle of the flexator when deflated (rad).

Assuming the flexator wall to be inelastic:

$$\text{flexator perimeter} = 2 \pi R_h = 2 W + a \pi \quad (5.56)$$

Where:

$R_h$  = radius of the fully inflated flexator hose when unfolded, and

$a$  = the thickness of a partially flattened flexator.

Assuming that both  $a$  and  $W$  are constant and that the straightening of the flexator occurs as an unrolling action away from the outer tube, then:

$$\text{Change in the radial contact length} = a \pi = R (\gamma - \alpha) \quad (5.57)$$

Combining the above equations gives the theoretical torque equation for a single flexator actuator as:

$$T = \left( \frac{P R r}{2 \cos \left( \frac{\pi - \gamma}{2} \right)} \right) \cdot \left( \pi R_h - R \left( \frac{\gamma - \alpha}{2} \right) \right) \cdot (1 - \cos \alpha) \quad (5.58)$$

Therefore for a dual flexator actuator:

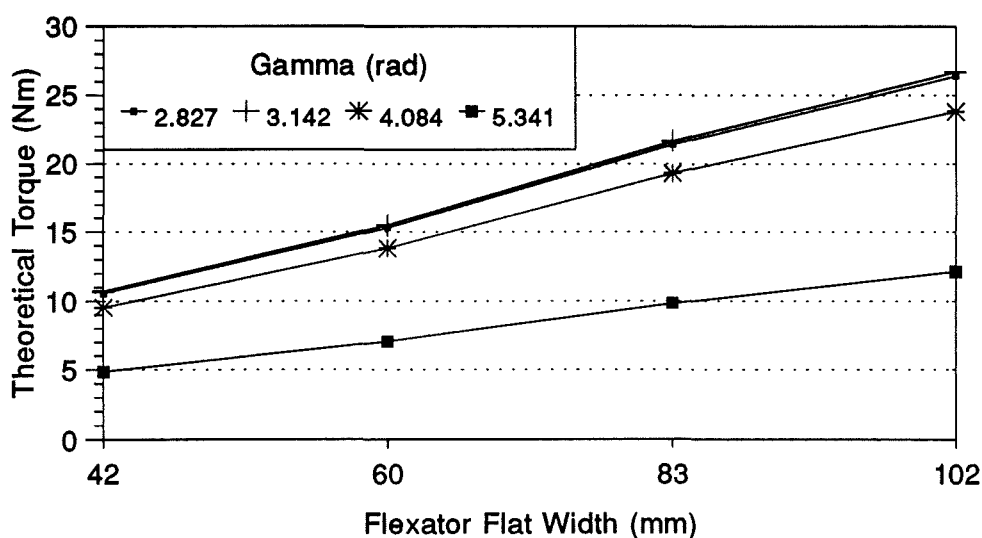
$$\lambda = T_1 - T_2 \quad (5.59)$$

The theoretical flexator torque decreases approximately linearly as the flexator inflates (only for the special case when  $\gamma \leq 180^\circ$ ). This torque reduction can be minimised by increasing the flexator's flat width,  $W$  in relation to the outer tube radius,  $R$ .

As illustrated in Section 5.4.1.1 the flexator actuator exhibits a large degree of hysteresis. Some of the causes of this have already been discussed, however, observations have shown that flexator actuators with large wrap around angles ( $\gamma > 180^\circ$ ) can produce high torques, however, they also exhibit large hysteresis values, as high as 97% (see Appendix F2). A considerable amount of this hysteresis is caused by the flexator buckling and kinking, producing high frictional effects between the flexator, webbing strap and outer tube.

By appropriate choice of the actuator variables a compromise solution can be reached whereby the frictional, and hence hysteresis effect is minimised and the output torque is maximised, ie increasing the width of the flexator (to give more torque) instead of the length. Also by having a smaller inner drive shaft radius, the movement of the flexator would be less for a given stroke. However, this would also reduce the torque.

$$P = 6 \text{ bar}, R = 31.75 \text{ mm}, r = 14 \text{ mm}$$



@ alpha = gamma

Figure 5.32 - Variation of theoretical torque with wrap around angle and flat width.

Figure 5.32 shows the variation of theoretical torque with different values of wrap around angle,  $\gamma$  and flat width sizes of flexator. By modifying the design parameters of equation 5.58 it is possible to specify the desired torque output of the flexator actuator for any given application. The flexator can produce very large torques from low mass, low cost actuators.

The larger the wrap around angle,  $\gamma$  the lower the initial torque value, ie when  $\alpha = \gamma$  (flexator pressurised but not inflated). However, when the flexator begins to inflate the theoretical torque output will increase, reach a peak value and then begin to decrease and may exceed the maximum torque of flexators with lower wrap around angles (see figure 5.33). The theoretical output torques actually follow a sine wave characteristic whose phase shift is determined by the wrap around angle,  $\gamma$ .

The ratio of the contact angle,  $\alpha$  to the angular displacement,  $\theta$  of the inner drive shaft, determined experimentally, has a value of between 1:2.15 (Tillett, 1993) and 1:3.3 depending on the actuator size. For the size of actuator used in these tests, the ratio was approximately 1:3.3.

$$P=6 \text{ bar, } R=31.75 \text{ mm, } r=14 \text{ mm}$$

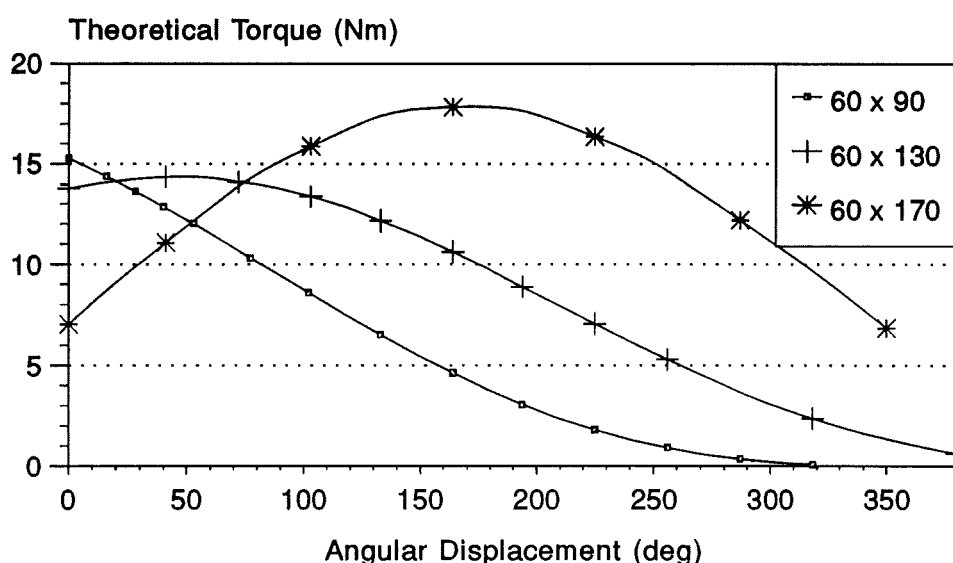


Figure 5.33 - Sine wave theoretical torque output of the 60 series flexator actuator.

### 5.6.8 Simulation Results

The ACSL simulation program was written in three versions, a basic model which consisted of no flow into or out of the drive chambers, a unidirectional model with no feedback (open loop), and a full model (bi-directional) with a proportional error feedback loop (see Appendix K). The first model provided information on how the actuator would react to an external force applied about its mean position ( $\theta = 0^\circ$ ). The second model enabled matching of the flexator/webbing strap frictional constants with the results from experimental testing. The third model which incorporated these frictional constants, enabled testing of the P.E. control algorithm and also provided predictions of the actuator's performance for different system variables.

#### 5.6.8.1 Determination of the flexator/webbing strap frictional constants

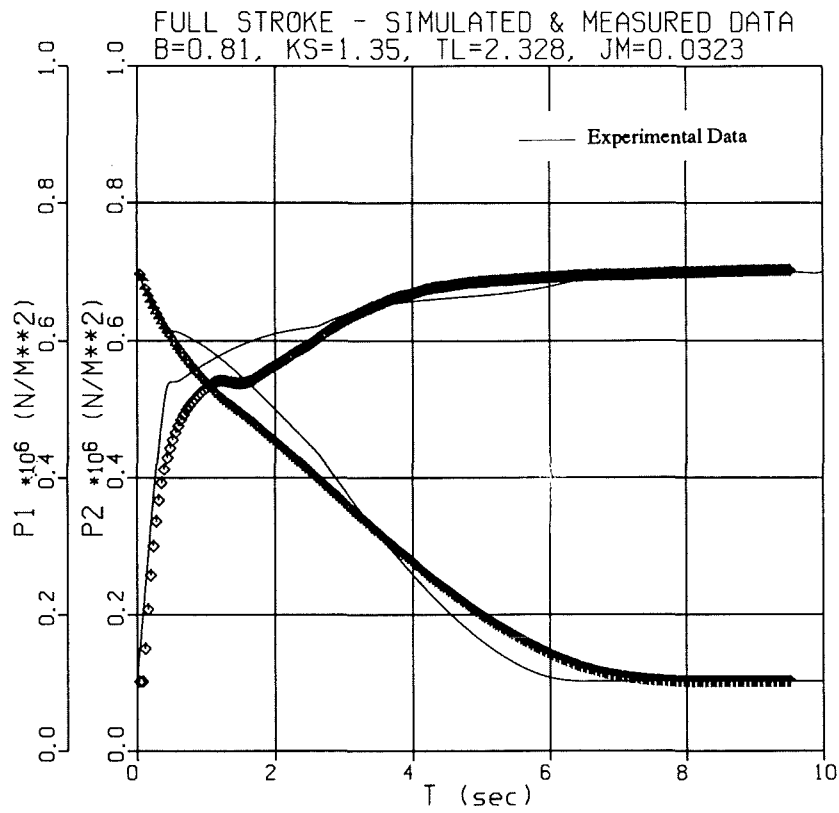
As in Section 5.6.6 the static and viscous frictional torque constants had to be found for the flexator and webbing strap combination. The static frictional torque term used in the simulation program consisted of a function whereby the frictional torque of one flexator was a maximum at the end of stroke position (fully inflated), at this point the frictional torque for the second flexator was a minimum (fully vented), the constant,  $KS$  being used to control the function's maximum value (see Appendix K). Using this function, as the actuator moves between the end of stroke positions, the frictional torque changes linearly, it being the absolute sum of the frictional torques from each flexator/webbing strap combination multiplied by the sign of the angular velocity. The static frictional torque function therefore varies with  $\theta$  and appears to be a combination of static and coulomb frictional torque. The viscous frictional torque function was much simpler to calculate and consisted of a constant,  $B$  multiplied by the angular velocity.

$$\text{Viscous frictional torque function, } FD = B \dot{\theta} \quad (5.60)$$

$$\text{Static frictional torque function, } FS = \text{sgn } \dot{\theta} \cdot \text{abs}(F_1 + F_2) \quad (5.61)$$

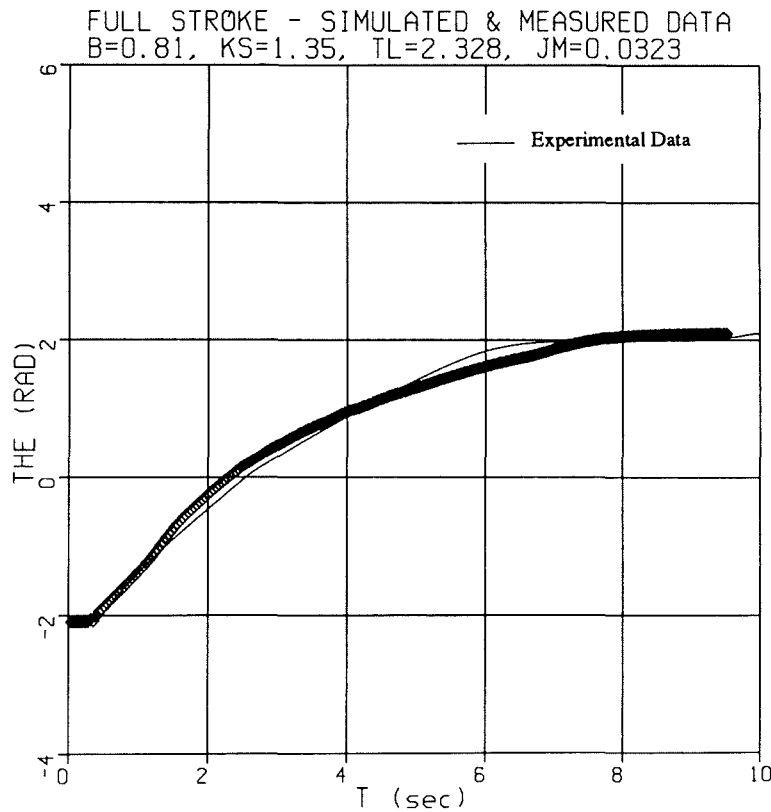
$$\text{Where } F_1 = \left( \frac{\theta + 2.1642}{KS} \right) \text{ and } F_2 = \left( \frac{-2.1642 + \theta}{KS} \right) \quad (5.62)$$

The simulation program used the known constants from the experimental test-rig to compute values for the output variables such as chamber pressures,  $P_1$  and  $P_2$ , mass flow rates,  $\dot{m}_1$  and  $\dot{m}_2$  and the angular displacement,  $\theta_{rad}$ . The frictional torque constants were then modified iteratively at run-time until the output variables were observed to match as closely as possible to the experimental data (see figures 5.34 and 5.35).



22 5-JUL-93 17:45:33

Figure 5.34 - Simulated and experimental chamber pressures (60 x 90 flexator).



21 5-JUL-93 17:45:33

Figure 5.35 - Simulated and experimental angular displacement data (60 x 90 flexator).

From the above analysis the static and viscous frictional torque constants have been evaluated for the flexator/webbing strap combination. The values of these constants have been found to be:

$$B = 0.81 - 0.0316 = 0.7784 \text{ (Nm sec rad}^{-1}\text{)} \text{ and } KS = 1.35 \text{ (rad Nm}^{-1}\text{)} \quad (5.63)$$

Thus the maximum static frictional torque occurred at the end of stroke positions and had a value of 3.2 Nm for this size of actuator. The maximum viscous frictional torque had a value of approximately 1.5 Nm and occurred at about 1 second into the simulation run.

Once the simulated and experimental data had been matched, the resulting frictional constants were then used in the full model (bi-directional) simulation, which incorporated a proportional error (P.E.) feedback loop. Simulation runs were then conducted by varying the load torque, inertia, deadband space and step input for each run. The deadband space was a region about the zero error line where the mass flow rate terms were set to zero. This prevented the system from hunting about the zero error position.

The simulated results could not however, be compared with experimental data due to the fact that the new control algorithm had not been implemented on the test-rig configuration at the time of writing this thesis (see Appendix K).

## 5.7 CONCLUSIONS

The physiological analysis of human muscle, explaining its operation within the human skeletal system provided a source of valuable information. A figure of 45% has been quoted for the peak efficiency of a human muscle powered joint.

The review of previous work on pneumatic muscle type actuators, which mimic human muscle, has shown that systems of this nature have been around for over thirty-five years, however, to date very few of these systems have found widespread use. Part of the reason for their lack of success lies in the fact that all of these systems are linear type actuators, which were then used to form rotary type joints. Since the majority of robotic devices use rotary joints, this is an important factor in favour of the only rotary type pneumatic muscle actuator, the flexator.

The theory of controllable compliance has been stated and its special significance to rehabilitation devices has been demonstrated. The flexator rotary actuator has been introduced and experimental data on its performance presented. From this data, a

comparison with other direct-drive rotary actuators was conducted and the flexator actuator was found to have a very high peak torque to motor mass ratio, comparable with all but the largest actuators, and one of the lowest in terms of cost.

The theoretical analysis of the flexator actuator using the non-steady flow energy equation gave a simple equation relating angular displacement to the pressure and volume of the flexator, its load torque and efficiency. The limiting conditions of this equation have been stated. Since the efficiency of the flexator was found to be variable and related to the flexator size and load torque the usefulness and accuracy of this equation as applied generally was questioned.

Extensive testing of the single flexator actuator revealed its operating characteristics and problems due to the presence of large hysteresis. Investigations into this problem have pointed to several possible causes, some of which can be reduced by careful selection and design of the flexator actuator, and others which can only be reduced by changing the material properties of the flexator and webbing strap.

By using dual flexator actuators, double-acting control of a revolute joint can be achieved. By varying the pressure in the dual flexator actuator, the compliance of the joint can be modified whilst maintaining its angular position. This is a feature particularly useful in a rehabilitation manipulator where the tasks and orientation of the arm are constantly changing.

Finally, the simulation program has enabled the flexator's frictional torque constants to be evaluated, and by using these newly found constants in the full model, predictions have been made on the performance of the dual flexator actuator for different sets of system constants. Errors between the simulated and experimental values exist, due to the complex nature of the actuator, the simple friction and flow functions used in the simulation and the assumptions made to simplify the analysis. However, these are small and could be reduced further if more sophisticated functions were to be used.

The following chapter describes how the results of the design specification from chapter 4 influenced the kinematic design of the wheelchair-mounted manipulator. From an analysis of the critical criteria, a novel kinematic arrangement was designed which combines the best features of several different industry standard robots. Finally parametric design techniques have been used to establish the dimensions of the links and the strokes of each joint, in order to perform the tasks required by the intended users.

# Chapter 6

## KINEMATIC DESIGN OF THE MIDDLESEX MANIPULATOR

---

*'I am going to dine with some men. If anybody calls  
Say I am designing St Paul's.'  
Sir Christopher Wren 1632-1723.*

---

### 6.1 INTRODUCTION

The kinematic arrangement of the rehabilitation manipulator will to a large extent determine whether the design will be successful in accomplishing the tasks selected by the intended users. In determining the best kinematic arrangement many aspects of the overall 'user experience' have to be considered, which includes the design criteria listed in the final design specification.

#### 6.1.1 Needs of the User

The needs of the user were obtained from the questionnaire survey and the reviews of previous wheelchair-mounted rehabilitation projects, these directly influenced the design specification for the manipulator. This in turn gave a perception of what the ideal manipulator would be like in terms of its design, configuration and features. However, only some of the criteria in the design specification directly influenced the design of the kinematic arrangement, these are listed below:

- *Be able to lift at least 1 kg anywhere within its working envelope;*
- *Be able to reach down to the floor level and up to a shelf at 1.7m;*
- *Be capable of reaching to a zone in front of the operator from head to thigh;*
- *Be easy to control (minimum number of joints);*
- *Have a low cost (less than £3,000);*
- *Have a low mass (less than 8 kg);*
- *Be dextrous;*
- *Be aesthetically pleasing;*
- *Fold away into a compact unit below the armrest (home position);*
- *Conserve energy when at rest;*



- *Be able to be used outdoors (waterproof);*
- *Have a kinematic configuration which under normal use is stiff in the vertical plane and compliant in the horizontal plane;*
- *Be designed with reference to the top eighteen tasks (see Table 3.2);*
- *Not make the wheelchair any wider or longer (in order to maintain accessibility);*
- *Have reprogrammable memory locations for frequently used tasks (joint feedback);*
- *Have speed control of individual joints and*
- *Be safe in use (not injure the user or any other person).*

Some of the above criteria have a greater influence on the kinematic arrangement than others, however, all are important when determining the best kinematic design. Many different kinematic arrangements were evaluated before a decision was made to proceed with a particular design. Studying the first three degrees of freedom of a robot indicates that the various combinations of rotation and translation joints can produce 42 different kinematic arrangements (Coiffet, 1987). However, a review by Liegeois and Dombre in 1979 showed that of 115 industrial robots surveyed only five types of kinematic arrangement were used. A more recent survey of assembly robots in Japan (Mortimer, 1991) shows the importance of the SCARA geometry (see figures 6.1a & 6.1b).

The initial conceptual designs for the kinematic arrangement were based on the following five standard industrial robot geometries:

- *Articulated (PUMA : Programmable Universal Machine for Assembly);*
- *Horizontally articulated (SCARA : Selective Compliance Assembly Robot Arm);*
- *Cartesian (x, y, z);*
- *Spherical ( $\theta, \phi, r$ ) and*
- *Cylindrical ( $\theta, z, r$ ).*

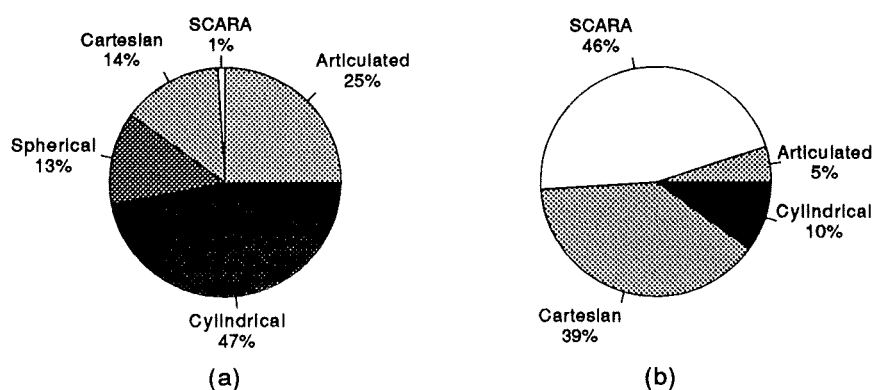


Figure 6.1 - Surveys of industrial robot geometries.

From observation of the joint structure and workspace of the above geometries, together with knowledge of the wheelchair application, it soon became clear that some geometries were incompatible with the application and could not fulfil the needs of the user as listed above. The geometries rejected at this stage were the cartesian and the spherical, this was mainly due to the requirements to reach down to the floor level, reach up to a shelf height of 1.2m and also to have a compact home position. It also became clear that no single geometry could fulfil all the user requirements, and that a combination or hybrid of two or more geometries could form the ideal kinematic arrangement.

Due to the success of SCARA type robots, such as the RTX (see figure 6.2), in rehabilitation applications, a detailed investigation of this arrangement was conducted.

### 6.1.2 The SCARA Geometry

Developed during the period 1978-81 by researchers at the Faculty of Engineering, Yamanashi University Japan in collaboration with a consortium of industrial companies, the SCARA robot has been a revelation. Its popularity has increased rapidly; used almost exclusively today for flexible automation in the assembly process due to its many advantages over traditional methods of assembly and improved performance over other types of industrial robot (Makino & Furuya, 1980; Makino et al, 1980; Makino & Furuya, 1981; Makino & Furuya, 1982).

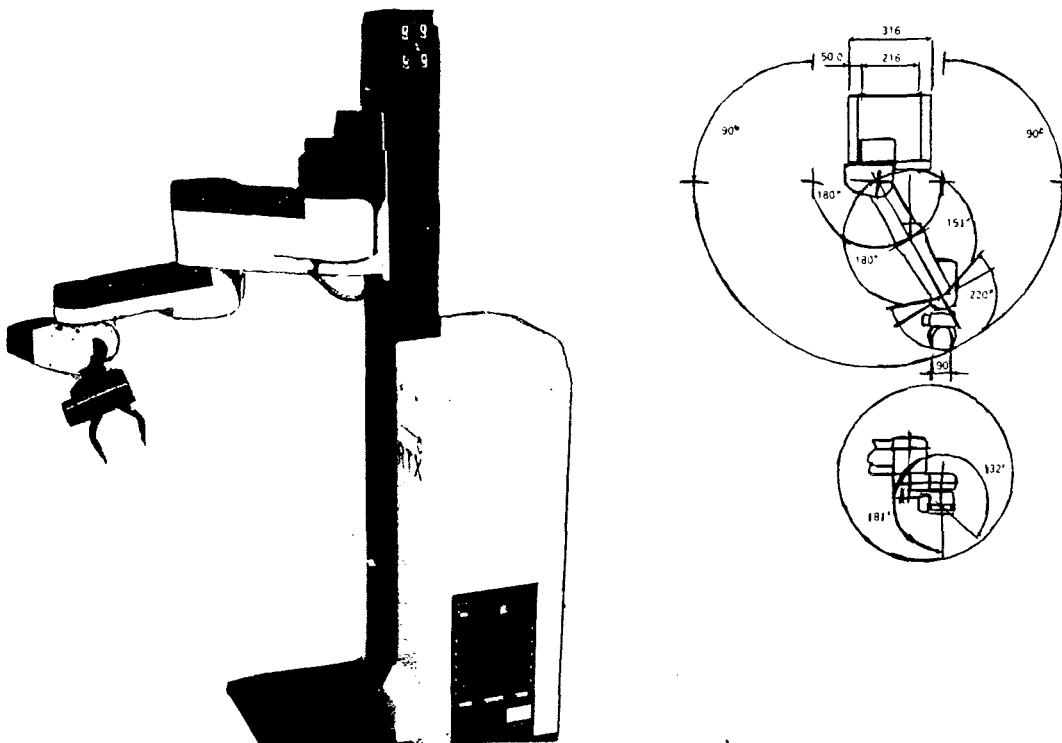


Figure 6.2 - RTX Robot showing SCARA Configuration (UMI Ltd)

Industrial SCARA robots typically have excellent horizontal manipulation but poor vertical travel, usually the end effector in this configuration is the only part of the arm that moves in the vertical direction, and this to only a limited stroke. Even so, the workspace of this type of robot has been stated to be ten times that of a cartesian geometry robot of the same size (Makino and Furuya, 1982). The major joints do not oppose gravitational forces and can therefore be of small torque ratings. Due to the arrangement of jointed planar linkages, the actuators can either be of the direct-drive type, or mounted in-board and driven through belts or chains. This lowers the moment of inertia of the links and the bending moment of the arm about the base joint. The workspace of the SCARA robot is in the form of a heart shape, which would suit the wheelchair application where the need is to reach to the user as well as to the front and side of the wheelchair.

SCARA robots are now almost exclusively used by the electrical component assembly industry, where the specifications call for high-speed, low component masses, high repeatability and horizontal compliance. The ability to be stiff in the vertical plane and compliant in the horizontal plane enables it to perform tasks involving insertion of components, such as mounting electrical components onto a circuit board. The compliant nature of the SCARA robot in the horizontal plane is also an important safety feature when in close proximity to the user, as in a rehabilitation robotic application.

### 6.1.3 The Wheelchair-Mounted Application

The wheelchair-mounted application imparts certain constraints on the robot geometry and its associated workspace. The conflicting requirements, to be able to reach to the floor level as well as to a height of 1.7m, caused many problems when trying to match these needs to the workspace of the proposed robot.

As mentioned previously, the industrial SCARA robot is mainly designed to perform tasks involving pick, place and insertion operations where the vertical travel is small compared to the large horizontal workspace; for this arrangement the optimum solution is to place a prismatic vertical joint (stroke  $\leq 0.3\text{m}$ ) directly on the axis of the end effector. In the rehabilitation setting there is a similar need for a large horizontal workspace, but there is also a need for a large vertical stroke. Using the industrial SCARA geometry and making the vertical stroke at the end effector larger is impractical, due to the related negative effects that the extra size and mass would cause. The RTX and the BIME robots overcome this problem by having prismatic base joints which act vertically and have strokes of 0.915m and 0.42m respectively. However, both these arms were designed for the workstation environment where space is not as limited as in a mobile system.

In the wheelchair application, the space criteria dictates that the whole of the arm parks in a position that is beneath the armrest and which does not make the wheelchair substantially wider or longer. It is obvious that the high reach characteristic (reach up to 1.2m) could be achieved with a fixed pillar arrangement, upon which the whole arm was raised, as in the RTX design. However, this would prevent the arm being parked, cause visibility problems for the wheelchair user and would be unlikely to be accepted; this concept was therefore rejected.

Another possible solution involved a multi-jointed telescopic base which would support the whole arm allowing it to reach to the floor as well as to a height of 1.2m, and also have a compact park position beneath the armrest (see figure 6.3). However, after initial optimism, the design could not be prototyped due to the fact that no industrial telescopic actuator of sufficient stroke and small unextended length could be located. Initial designs of a purpose-built unit indicated great difficulties in the manufacture, construction and cost of such an actuator, and the concept was therefore filed, until such time as an actuator of this type became available.

Alternative design solutions combining one or more of the basic kinematic arrangements were then considered. Combining the advantages of the SCARA configuration with the vertically articulated arm seemed to give an optimum solution to the twin problems of reach and suitable workspace. The next stage was to incorporate the advantages of both kinematic arrangements into a new hybrid system designed specifically for the wheelchair-mounted configuration.

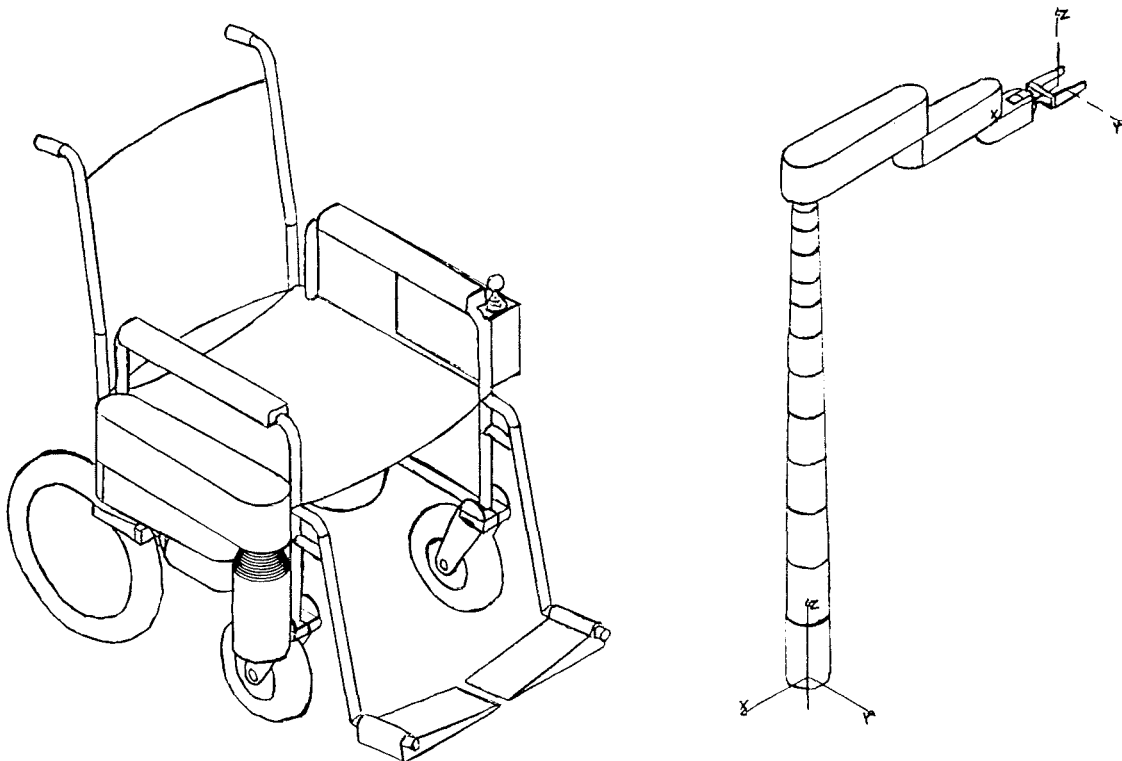


Figure 6.3 - SCARA concept with telescopic z-axis.

### 6.1.4 The Scariculated Arm Design

After considering many possible design solutions to the problem, it was decided to combine the advantage of large vertical stroke from the vertically articulated geometry with the advantage of large horizontal stroke from the SCARA geometry. This has been achieved by inserting a  $\pm 90^\circ$  joint at the beginning of the first link of a standard SCARA design. The arm is thus enabled to reach to the floor ( $-90^\circ$  position) in the vertically articulated mode (see figure 6.4) and up to a high reach ( $+90^\circ$  position) also in the vertically articulated mode by the use of this extra joint; with the  $0^\circ$  position being the normal SCARA mode. The scariculated design consists of seven joints and the end effector grasp (five rotary and two linear) (Prior & Warner, 1991).

The kinematic arrangement selected for the prototype design is therefore a hybrid combination of the SCARA geometry and the vertically articulated geometry. It is proposed to call this new type of geometry the SCARICULATED arm geometry.

#### 6.1.4.1 Design philosophy and control

The basis for the design philosophy of the scariculated arm geometry is that for the majority of its normal working cycle, the arm would be operating in the SCARA mode within a zone to the front and side of the wheelchair user, from their head down to their

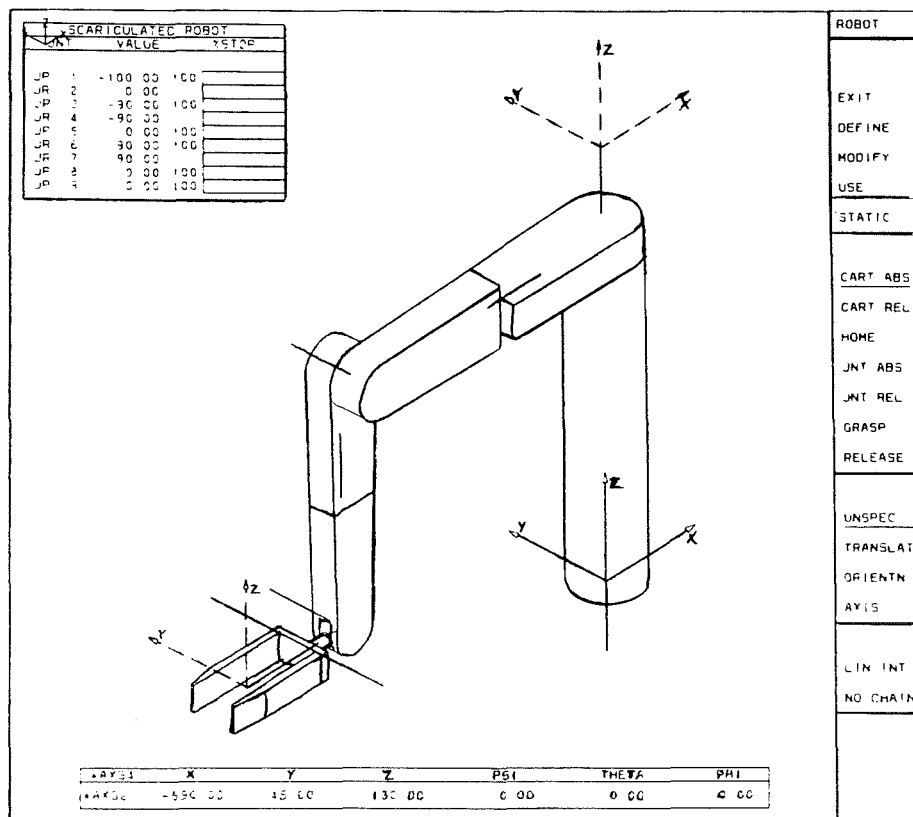


Figure 6.4 - Scariculated arm geometry, designed using CATIA

thigh height. These operations would form typical pick and place tasks, working environment tasks and personal hygiene tasks. To simplify the control structure presented to the user, the design philosophy envisages that the user would control a maximum of two joints at any one time. This ties in with the coarse/fine control strategy defined earlier, in other words when the arm is being controlled manually, the user would first position the height of the arm (z-coordinate), then the two main rotary joints would be controlled to coarsely position the arm in x-y space, and finally the user would control the fine movement of the end effector by controlling the two degrees of freedom at the wrist.

## 6.2 PARAMETRIC DESIGN OF THE SCARICULATED ARM GEOMETRY

Once the basic concept of the scariculated arm geometry had been established there then followed a detailed design phase whereby dimensions/strokes were placed on the individual components in the design. This stage of the design process was iterative, taking many loops before an optimum solution was reached. However, it was recognised that the design solution would be modified by problems associated with the manufacturing process. Figure 6.5 shows a schematic diagram of the scariculated arm design detailing the parameters within which the arm must perform and the variables which can be modified in order to meet the design requirements.

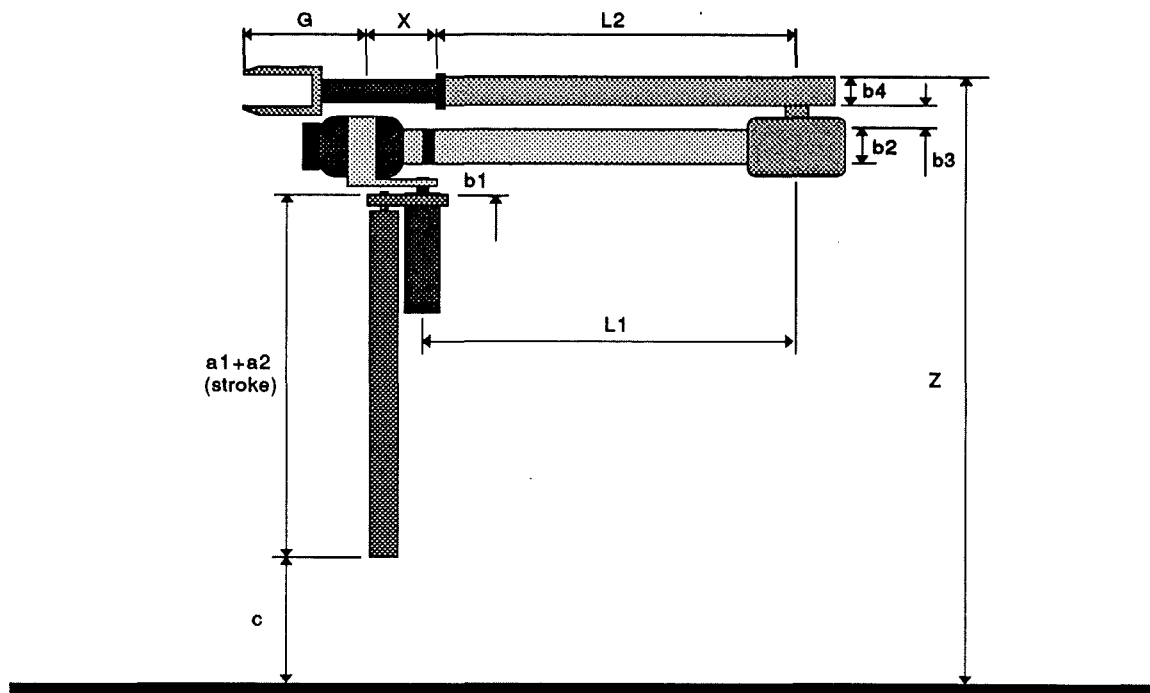


Figure 6.5 - Parametric design of the scariculated arm.

The labels used in figure 6.5 are classified below:

- $a1$  - length of the vertical lift actuator;
- $a2$  - stroke of the vertical lift actuator;
- $b1$  - clearance between the top of the vertical lift actuator and the first robot link;
- $b2$  - diameter of the first robot link;
- $b3$  - clearance between the two robot links;
- $b4$  - diameter of the second robot link;
- $C$  - wheelchair's front castor clearance height (220mm);
- $G$  - length of end effector and wrist;
- $L1$  - length of link 1 from the axis of joint 2 to the axis of joint 4;
- $L2$  - length of link 2 from the axis of joint 4 to the end of the link;
- $x$  - length of the extension of joint 5, and
- $Z$  - overall height of the robot arm from the floor level.

At this point in the design process the only physical dimensions available were the wheelchair's front castor clearance height (220mm), the average armrest height (737mm) and the average seat depth (410mm) (see Section 1.3.2). Placing the robot's base joint at the front corner of the wheelchair allowed good reach and workspace, but also meant that the base could not be placed lower than 220mm from the floor level, due to interference with the motion of the castor. The robot's base joint could be placed lower if it were outside the range of motion of the castor, however, this would cause the width of the wheelchair to be increased beyond that which was acceptable.

### 6.2.1 Parametric Equation Definitions

- *Home height ( $Z$ )*

$$Z = C + a1 + b1 + b2 + b3 + b4 \quad (6.1)$$

- *Floor reach ( $\theta_2 = -90^\circ$ )*

$$C + a1 + b1 + \left(\frac{b2}{2}\right) = L2 + x + G \quad (6.2)$$

- *Max vertical reach ( $V_r$ ) (normal SCARA mode)*

$$V_r = C + a1 + a2 + b1 + b2 + b3 + \left(\frac{b4}{2}\right) \quad (6.3)$$

- *Max vertical reach ( $Vr_{\max}$ ) ( $\theta_2 = +90^\circ$ )*

$$Vr_{\max} = C + a1 + a2 + b1 + \left(\frac{b2}{2}\right) + L2 + x + G \quad (6.4)$$

- *Max horizontal reach ( $Hr_{\max}$ ), assuming  $\theta_3 = 180^\circ$*

$$Hr_{\max} = L1 + L2 + x + G \quad (6.5)$$

### 6.2.1.1 Initial values for the design variables

By assuming some initial values for the design variables, it was possible to determine the lengths of the two main links L1 and L2, so that the arm could meet the design requirements and to see how these parameters affected the other characteristics. However, the overall concern of the designer of a robot must be to make the length of the links and the stroke of the actuators just enough to fulfil the workspace requirements, remembering that redundant length means added inertia, and redundant stroke means the possibility of collisions and singularities.

As in the human arm, balance and aesthetics are essential; therefore the robot arm should also be balanced in size and shape, and aesthetic in form. Having reviewed the design of the human arm in section 1.3.1.1 some of these elements can now be applied to the design of the manipulator. The ratio of lengths of the two links L1 and L2 should be approximately 1.1:1 and the ratio of the length of the arm (L1+L2) to the length of the end effector should be approximately 2.8:1. The robot arm should also appear to taper from the shoulder joint to the end effector, i.e.  $b2 > b4$ .

$$\frac{L1}{L2} \approx 1.1 \quad (6.6)$$

$$\frac{L1 + L2}{G} \approx 2.8 \quad (6.7)$$

$$b2 > b4 \quad (6.8)$$

After many iterations of altering the design parameters and calculating the resultant link lengths and reach characteristics, the optimum design solution was reached which encompassed most of the design requirements, in the most economic manner. The final design parameters are shown in Table 6.1. Throughout the design process compromises had to be made in terms of the maximum vertical reach, the maximum vertical SCARA



reach and the number of configurations by which the arm could reach down to the floor level.

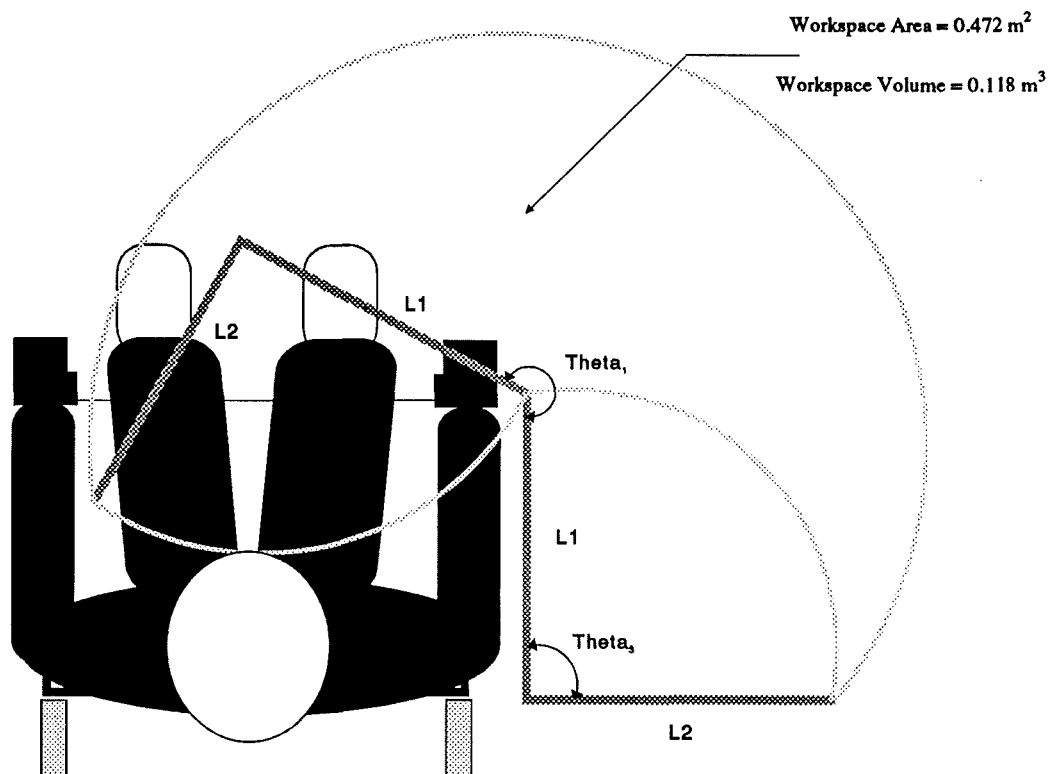
**Table 6.1 - Parametric Design Variables and the Optimum Solution.**

| a1  | a2  | b1 | b2 | b3 | b4 | C   | G   | L1  | L2  | x   | Z   | V <sub>r</sub> | V <sub>rmax</sub> | H <sub>rmax</sub> |
|-----|-----|----|----|----|----|-----|-----|-----|-----|-----|-----|----------------|-------------------|-------------------|
| 396 | 250 | 10 | 50 | 15 | 40 | 220 | 220 | 364 | 331 | 100 | 731 | 961            | 1552              | 1015              |

It was realised at this stage that the optimum solution for the design variables given above would need to be flexible enough to cope with problems in the manufacturing process and the availability of materials and components, etc.

### 6.2.2 The Scariculated Workspace

Having established the optimum solution for the design variables the following stage analysed what actuator stroke would be required for each joint in order to perform the desired tasks and fulfil the workspace requirement. In the normal SCARA working mode, the arm would have to be able to operate in a zone to the front and side of the wheelchair user, from their head down to their thigh height. As a first approximation, this workspace could be obtained by having the stroke of the first rotary joint ( $\theta_1$ ) from  $0^\circ$  to  $225^\circ$ , and the stroke of the third rotary joint ( $\theta_3$ ) from  $0^\circ$  to  $360^\circ$ .



**Figure 6.6 - Plan view of scariculated workspace geometry.**

However, as stated previously, it is desirable to limit the joint strokes as much as possible. The minimum stroke for  $\theta_1$  cannot be reduced due to the working envelope required, but the stroke for  $\theta_3$  could possibly be reduced to an absolute minimum of  $90^\circ$ ; any less would not allow the arm to reach to the floor when the mode change joint is activated ( $\theta_2 = -90^\circ$ ). This would have the effect of limiting the horizontal reach, but as figure 6.6 shows it could improve the usability of the system, reduce the torque required from  $\theta_1$  and prevent singularities.

Table 6.2 below shows the joint strokes for each actuator in the scariculated arm geometry as detailed above, including the two proposed wrist joints and the end effector maximum opening.

Table 6.2 - Joint Strokes for the Scariculated Arm Geometry.

| a2         | $\theta_1$       | $\theta_2$     | $\theta_3$      | x          | $\theta_4$       | $\theta_5$       | Grip      |
|------------|------------------|----------------|-----------------|------------|------------------|------------------|-----------|
| 0 to 250mm | 0 to $225^\circ$ | $\pm 90^\circ$ | 0 to $90^\circ$ | 0 to 100mm | 0 to $360^\circ$ | 0 to $180^\circ$ | 0 to 80mm |

### 6.3 CONCLUSIONS

This chapter has reviewed the needs of the user and utilised the information derived from the questionnaire survey and design specification to form the basis of a new design of rehabilitation manipulator which combines the best features of the SCARA and vertically articulated robot geometries. By using CAD modelling and parametric design techniques, an optimum design solution has been reached which meets the majority of the design requirements in the most efficient way. The optimum design variables in terms of lengths and strokes of the scariculated arm geometry are set out as guidelines upon which the prototype design would be based, these guidelines must be flexible enough to cope with problems relating to the manufacturing process and as such could change as the design evolves.

The following chapter introduces the design and development work carried out on the prototype arm, from an initial sight model through to two versions of a fully functional working system. Design, manufacture, testing and analysis of all the mechanical and pneumatic components are discussed together with the design of the user interface, controller and implementation of the control strategy.

# Chapter 7

## DESIGN & DEVELOPMENT OF A MULTI-AXIS PROTOTYPE ARM

---

*'I have called this principle, by which each slight variation, if useful, is preserved, by the term Natural Selection.'*  
Charles Darwin, 1871.

---

### 7.1 INTRODUCTION

This chapter reviews all of the design and development work carried out during the realisation of a working prototype stage. This stage involved many smaller sub-stages which consisted of the following:

- *Construction of a full-sized sight model;*
- *Selection of the most appropriate actuator for each joint;*
- *Design, construction, testing and evaluation of a first prototype arm and controller;*
- *Flexator actuator control philosophy;*
- *Experimental & theoretical analysis of control valve fluid flow, and*
- *Construction & testing of a redesigned, second prototype arm.*

### 7.2 FULL-SIZED SIGHT MODEL

To verify the kinematic arrangement of the Middlesex manipulator, as well as to enable the visual inspection and critique of the design, a full-sized sight model was constructed and mounted on an electric wheelchair (Prior et al, 1992a).

The model was made from standard plastic drain pipe & gutter materials. Ancillary mounts and clamps, etc were machined from Nylon-66 and Aluminium alloy. The model was fully functional with all eight joints, including the end effector grip/ungrip, able to move according to the specifications detailed in Table 6.2. The arm was mounted on a hinged door, which was in turn mounted at the side of an electric wheelchair (see figure 7.1). The hinged door was necessary to allow the arm to be swung away from the wheelchair when the user needed to move from the wheelchair to a chair, toilet or into a

vehicle. Due to the need to produce the model quickly and at low cost, it was not always possible to match the specified component diameters/lengths with commercially available materials, therefore some of the characteristics of the model, ie home height, etc, were larger than that required by the design specification. However, the ability to physically look at the arm in three dimensions and move all the joints, provided an invaluable source of information (Prior, 1993b).

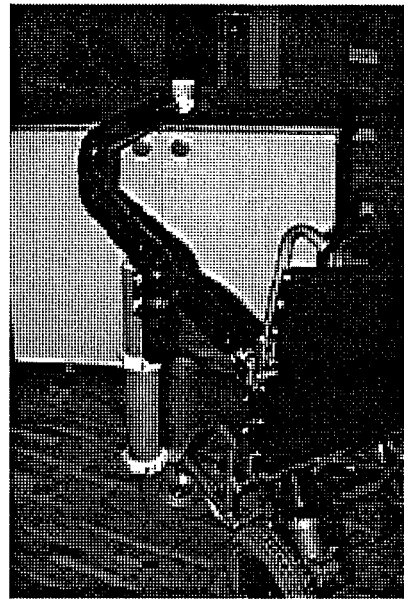


Figure 7.1 - Full-sized sight model.

The lessons learned from this exercise were that the size of the arm ie, the actuators and the diameter of the links, needed to be as small as possible, and that the mass of the arm would be critical. Even when constructed from lightweight plastics the arm produced problems associated with large moments about the first prismatic joint. It was also possible to analyze the workspace of the arm, the joint strokes required and determine whether the link lengths were correct.

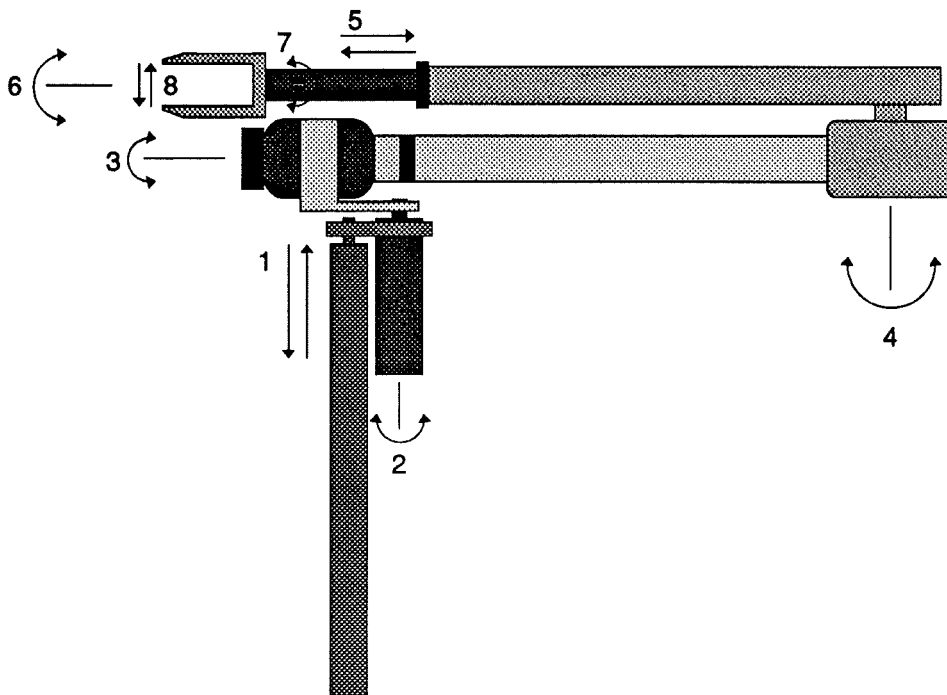


Figure 7.2 - Prototype arm's joint arrangement.

### 7.3 SELECTION OF THE PROTOTYPE'S JOINT ACTUATORS

Each axis of the prototype arm, as shown in figure 7.2, was analyzed in terms of its performance requirements, in order to determine the most appropriate type of actuator for each joint. As well as the performance requirements, the actuator review in Section 5.2 also used cost, availability and standardization of the working medium as some of its criteria.

#### 7.3.1 Joint 1 - Vertical Lift Actuator

This must be able to lift the entire arm, plus any payload, through a vertical stroke of 250 mm at a velocity of between 50 to 100 mm/sec. The actuator should also be of minimum mass (< 2 kg) and have a retracted height of less than 400 mm. When not in use the actuator should conserve energy, and be capable of maintaining a position within  $\pm 5$  mm under full load for a period of 24 hours. The actuator when fully extended should be capable of resisting a maximum turning moment in the vertical plane of at least 30 Nm. The width of the actuator should not increase the wheelchair's width by more than 100mm. With these specifications in mind, a review of pneumatic, electrical and hydraulic linear actuators was conducted. Table 7.1 shows a comparison between these three main types of linear actuator.

Table 7.1 - Comparison of Commercially Available Linear Actuators.

| Type of Actuator                        | Description of the Actuator   |
|---|---|
| Pneumatic double-acting cylinder        | Compact, fast, lightweight and low cost (< £120)                              |
| Pneumatic rodless cylinder              | Requires a fixed length of stroke and has a limited bending moment capability |
| Pneumatic bellows type actuator         | High force, low cost, but large footprint                                     |
| Electrical solenoid                     | Limited stroke of up to 75 mm only  |
| Electric motor driven ball screw        | High force, but slow speed and high cost (> £400)                             |
| Electric motor driven telescopic pillar | High force, small height, but large mass and high cost (> £300)               |
| Hydraulic double acting cylinder        | Very high force, but large mass and high cost                                 |

From the above analysis, it was clear that of the actuators which matched the specification, the pneumatic double-acting cylinder had the best specification, was readily available and had the lowest cost. The main disadvantages of this type of actuator were associated with its compliance and lack of positional feedback. However, it is possible to fit a clamping unit to the cylinder to prevent movement of the joint when

stationary, and also to fit magnetic sensors or other devices (LVDT's) to give position feedback. A pneumatic double-acting cylinder was therefore chosen for joint 1. After reviewing many similar pneumatic cylinders from various companies, it was decided to use a DZH-32-250-PPV-A double-acting cylinder from Festo Pneumatic Ltd, due to its special design of non-rotating oval piston, rectangular cylinder barrel (small width) and adjustable end position cushioning. The cylinder can produce a thrust of 483 N at 6 bar, has a mass of 1.25 kg and a base dimension of 36 x 48 mm. The cost of the actuator (without foot mountings) was £120.

### 7.3.2 Joint 2 - Shoulder Joint Actuator

Required to be able to rotate the whole arm through an angle of 225° when the arm is carrying its maximum payload, and in any orientation. The 0° position refers to the home position, ie when the arm is parked, parallel with the wheelchair's armrest. The joint's speed should be selectable, and be in the region of between 0.5 to 2 rad/sec. The actuator should be of small size and mass (< 1.5 kg), and be of low cost. Appendix B reviews the performance of a large range of commercially available rotary pneumatic, hydraulic and electrical actuators, together with the flexator actuator. The advantages of the flexator actuator have already been outlined in Chapter 5, and it was therefore decided to incorporate this low cost actuator in the design of the first prototype, as the shoulder joint actuator. The flexator size chosen for this joint was the 60 x 130 type, which is capable of producing a torque of 4.55 Nm through an angle of approximately 210° at 3.5 bar gauge (see Appendix F1.5).

### 7.3.3 Joint 3 - Mode Change Joint Actuator

The purpose of this joint is to enable the arm to transpose from the SCARA configuration into the vertically articulated geometry, when required to reach down to the floor level or up to a high shelf. The actuator stroke is therefore  $\pm 90^\circ$ , with the 0° position being the normal SCARA mode. The actuator must be able to be locked in these three positions; it is not envisaged that the arm would be used in any intermediate position, though it is recognised that the arm's workspace would be increased, if it were able to do so. After reviewing the alternative actuators available, it was decided to use a flexator actuator, due to its compactness, low cost and low mass. The flexator size chosen for this joint was the 60 x 90 type, which was able to produce a torque of 3.44 Nm through an angle of 180° at 3.5 bar gauge (see Appendix F1.4). This meant that the mode change joint was constrained to operate only when link 2 was parallel with link 1, thus minimising the required joint torque.

### 7.3.4 Joint 4 - Elbow Joint Actuator

When the arm is being used in the SCARA mode this joint becomes the second main rotary joint, enabling coarse positioning of the end effector in the horizontal plane. The desired stroke of this joint, as stated in Section 6.2.2 was 360°, with an absolute minimum stroke of 90°. For the first prototype, it was decided to have a joint stroke of 360°. Again after reviewing the alternative rotary actuators available, it was decided to use a flexator actuator. The flexator size chosen for this joint was the 60 x 170 type, which was able to produce a torque of 5.65 Nm through an angle of 250° at 3.5 bar gauge (see Appendix F1.6).

### 7.3.5 Joint 5 - Wrist Extension Actuator

The requirement for this joint, was to have a stroke of 100 mm and be able to lift the wrist/end effector together with the maximum payload of 1 kg.

The whole actuator had to be able to be situated within the diameter of link 2, and when retracted within the length of link 2. Again, the mass and cost of the actuator needed to be low. Due to the fact that the first four actuators were pneumatic, this made the use of a miniature double acting pneumatic cylinder the optimum choice for this particular joint. After reviewing several cylinders from different companies, it was decided to use a DSN-12-100-P from Festo Pneumatic Ltd. This actuator had a mass of only 121 grams, a cost of £25 and measured  $\varnothing 13.3 \times 205$  mm. When used at 6 bar it had a return force of 38 N, enough to lift the wrist/end effector and max payload. The only disadvantage of this type of actuator was the lack of positional control, however, it was envisaged that this joint would be operated with visual feedback from the user, therefore removing the necessity for position sensing.

### 7.3.6 Joints 6, 7 and 8 - Wrist Yaw & Roll and End Effector Grasp.

These three joints were not incorporated into the manufacturing stage of the first prototype. This was due to the primary requirement, to quickly test the kinematic arrangement of the arm, in the SCARA and vertically articulated modes; this could easily be achieved without the wrist/end effector. However, the design specification required that the wrist had two degrees of freedom - Yaw ( $\pm 90^\circ$ ) and Roll ( $\pm 180^\circ$ ), and that from the task analysis phase of the project, the end effector opens to 80 mm. Because the wrist's roll joint precedes the yaw joint, the latter can be transposed into a pitch type joint when the wrist rolls through 90°. Thus alleviating the need for a third degree of freedom at the wrist. It is proposed that these three joints be driven by stepper

motors, thus enabling a compact, lightweight wrist/end effector which has positional feedback, and can be used for the fine positioning of the arm.

## 7.4 DESIGN OF THE FIRST PROTOTYPE ARM

Having established the prototype's kinematic arrangement, joint structure, actuator strokes and types, the next stage in the design process was to decide upon the structural components of the arm; the materials used and their method of manufacture. In parallel with the detailed mechanical design stage came the control system design, incorporating the user interface, control philosophy and high level programming (Prior et al, 1992b).

### 7.4.1 Detailed Mechanical Design

Because of the requirement to produce a one-off prototype for a specific application, which incorporated several novel actuators, this inevitably meant that a large number of tailor-made components needed to be manufactured. This stage of the project therefore consisted of designing all the manufactured components of the arm, which comprised of the following parts (see working drawings in Appendix L):

- *The connection between joint 1 and joint 2;*
- *Joint 2 - the 60 x 130 dual flexator actuator;*
- *The connection between joint 2 and link 1;*
- *The mode change bearing arrangement;*
- *Link 1 structure;*
- *Joint 3 - the 60 x 90 dual flexator actuator;*
- *The mounting arrangement of the joint 3 actuator within link 1;*
- *Potentiometer mounts;*
- *Joint 4 - the 60 x 170 dual flexator actuator;*
- *The connection between joint 4 and link 1;*
- *The connection between joint 4 and link2;*
- *Link 2 structure;*
- *The mounting arrangement of the joint 5 actuator within link 2;*
- *The connection between joint 5 and the extension tube, and*
- *The extension tube & end cap.*

The requirements for the material used to construct the arm were:

- *Low density;*
- *Machinability;*



- *Availability;*
- *Non-corrosive in a damp environment;*
- *Medium to high Structural strength, and*
- *Reasonably low cost.*

After reviewing several alternative materials, a decision was made to manufacture the structural components of the prototype arm from Aluminium alloy, unless there was a specific need for added strength, in which case a mild steel material would be used. At all times during the design and manufacturing process the emphasis was on maintaining structural rigidity with minimum material.

#### 7.4.2 Selection of the Link Enclosure Type

Alternative profiles for the prototype arm links, such as circular, square, rectangular, together with variations of these, ie ellipsoidal, conical, open section, etc, were evaluated. After investigating the possible use of these types of profiles, it was decided that due to the cost element, the cross-sectional shape of the links should be either circular or rectangular, and uniform in the third dimension.

A theoretical analysis was conducted by Rivin in 1988, in which he compared the influence of two cross-sectional shapes (hollow round and hollow square) on the bending and torsional stiffness of a robot arm link. Two cases were analyzed, firstly where the wall thicknesses of both cross-sections were the same, and secondly where the cross-sectional areas of both links were the same. The results of this work showed that for the first case, the square cross-section provides a 69% to 84% increase in rigidity (depending on the ratio of the outside  $\phi$  of the tube to the wall thickness) with only a 27% increase in weight. In the second case, for the same mass, a link with square cross-section would have between 40% to 56% higher stiffness. In addition this section would also have 43% to 76% larger internal cross-sectional area. The thicker the wall, the bigger is the difference. However, the design requirements associated with this particular application and kinematic arrangement are more important, and outweigh the above advantages of using a rectangular cross-section in favour of a circular one. The design requirements that influenced this decision are listed below:

- *The design requires that the actuator of joint 3 be placed within link 1;*
- *When the mode change joint is operated, link 2 must not clash with link 1;*
- *Rectangular sections are harder to machine than circular ones;*
- *The aesthetics of the arm would be compromised by using a rectangular section, and*
- *A rectangular section occupies more of the workspace than a circular profile.*

A decision was therefore made to use hollow circular cross-sectional profiles of straight length for links 1 & 2.

#### 7.4.2.1 Factors affecting the optimum design variables

Placing the 60 x 90 flexator actuator within the body of link 1, meant that the diameter of this section could not match the optimum design variable,  $b_2$  as listed in Table 6.1, ie 50 mm. Allowing space for the inflation of the flexators in joint 3, and to enable a standard sized drawn aluminium alloy tube to be used, it was decided to set the diameter of link 1 to  $2\frac{3}{4}$ " (69.85 mm) with a wall thickness of  $\frac{1}{8}$ " (3.18 mm). Once this dimension had been established it was possible to determine the diameters of link 2 and the extension tube. From the parametric design equation 6.8, the diameter of link 1 must be greater than link 2; manufacturers data gave a  $\phi 2\frac{1}{2}$ " (63.5 mm) tube as the next size down, the next size after this was a  $\phi 2\frac{1}{4}$ " (57.15 mm), both with a  $\frac{1}{8}$ " (3.175 mm) wall thickness. These sizes were therefore selected for link 2 and the extension tube respectively. The arm clearance parameters,  $b_1$  and  $b_3$  had to be increased by 5 mm each during the manufacturing process (see below). The design of link 1, incorporating the actuator and position sensor of joint 3 as well as the mode change bearing, meant that the length of link 1 had to be increased to 415 mm, from the original value of 364 mm. The above changes to the optimum design of the prototype arm meant that the parametric equations had to be recalculated to ensure that the arm was able to reach the desired workspace (see below).

From Equation 6.1:

$$Z = C + a_1 + b_1 + b_2 + b_3 + b_4 \quad (7.1)$$

$$Z = 220 + 396 + 15 + 69.85 + 20 + 63.5$$

$$Z = 784 \text{ mm}$$

From Equation 6.2:

$$L_2 = C + a_1 + b_1 + \left(\frac{b_2}{2}\right) - x - G \quad (7.2)$$

$$L_2 = 220 + 396 + 15 + \left(\frac{69.85}{2}\right) - 100 - 220$$

$$L_2 = 346 \text{ mm}$$

The home height ( $Z$ ) of the arm was therefore recalculated to be 784 mm, 53 mm above the optimum solution and 47 mm above the average electric wheelchair's armrest height. To enable this kinematic solution to reach to the floor level, the length of link 2 had to be increased to 346 mm, 15 mm more than the optimum solution, making the ratio of link lengths 1.2:1. These changes meant that the arm would have a slightly longer reach in the horizontal and vertical planes, but also a higher moment arm acting on the piston rod of joint 1, which caused some concern. The modifications to the optimum design (listed above) were regarded as an inevitable consequence of the manufacturing process, as stated in Section 6.3, and therefore an acceptable compromise solution. Table 7.2 below shows the set of design variables and how these affected the reach characteristics.

Table 7.2 - Parametric Design Variables and the First Prototype (see figure 6.5).

| a1  | a2  | b1 | b2    | b3 | b4   | C   | G   | L1  | L2  | x   | Z   | V <sub>r</sub> | V <sub>rmax</sub> | H <sub>rmax</sub> |
|-----|-----|----|-------|----|------|-----|-----|-----|-----|-----|-----|----------------|-------------------|-------------------|
| 396 | 250 | 15 | 69.85 | 20 | 63.5 | 220 | 220 | 415 | 346 | 100 | 784 | 1003           | 1582              | 1081              |

#### 7.4.3 Manufacture and Assembly of the First Prototype Arm

Wherever possible standard sized components and materials were purchased to save on ordering, delivery, machining time and cost. However, as already stated many of the components of the arm, such as the flexator actuators, had to be manufactured from new,

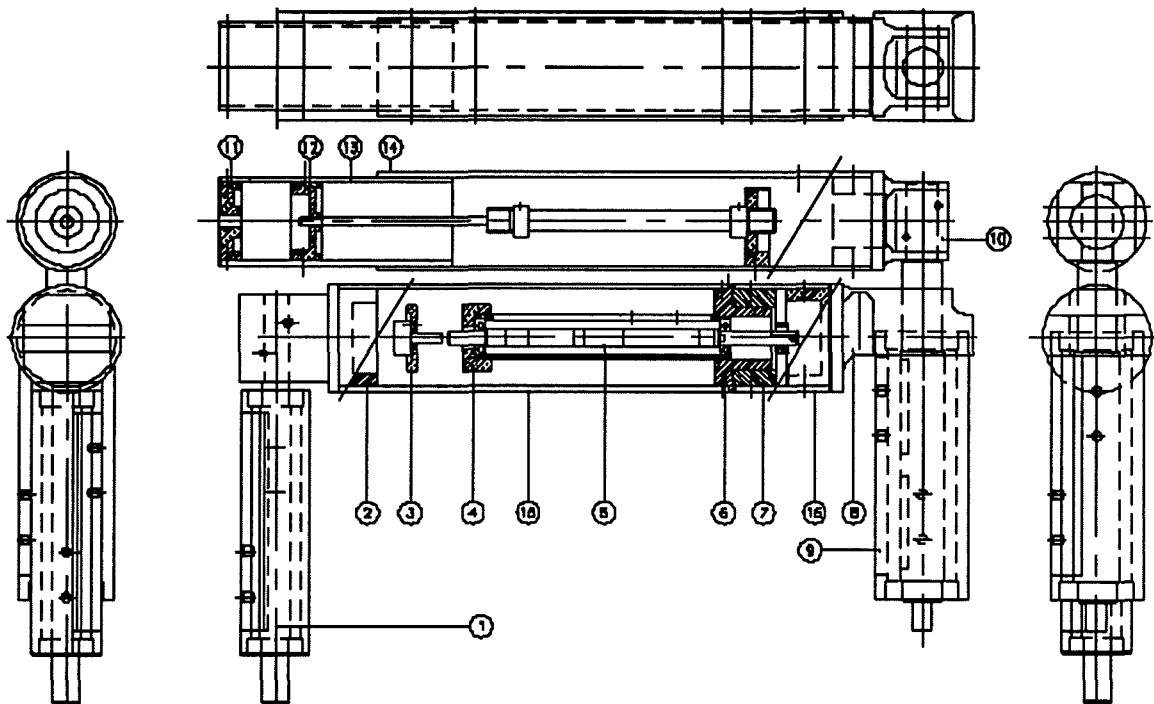


Figure 7.3 - Detailed design of the first prototype arm.

requiring considerable amounts of machining. The three versions of the dual flexator actuator used in the prototype were manufactured from Aluminium alloy, to the dimensions derived from the manufacture and testing of the flexator test-rigs (see Appendix M). The use of plastics or composites for the flexator actuator design was considered, but since the original flexator actuators were machined from steel, it was deemed prudent to first manufacture the actuators from Aluminium alloy and test their integrity before utilizing plastic/composite materials at a later stage.

The need for the arm to be stiff in the vertical plane placed limits on the design of the parts connecting the output shaft of joint 2 to link 1, joint 4 to link 1 and the output shaft of joint 4 to link 2. These connecting pieces were machined from Aluminium alloy bar of  $\phi 2\frac{3}{4}$ " (69.85 mm) and  $\phi 2\frac{1}{2}$ " (63.5 mm) respectively, to match the size of the tubes used for links 1 & 2. The drive shafts of joints 2 & 4 were machined to be an interference fit into the connecting parts, and were further pin-jointed to prevent any rotation of the shaft relative to the connection. All the components of the arm were designed and constructed to provide a stiff structure, which could be disassembled quickly, providing access to the arm, by the use of small countersunk hexagon head screws which held the main components of the arm together. Figure 7.3 shows the detailed design of the first prototype arm, without the vertical lift actuator or the wrist/end effector. In this figure some of the minor components have been omitted; a key to the numbered components is given below in Table 7.3 and working drawings for some of the major parts are given in Appendix L (see reference numbers in Table 7.3).

**Table 7.3 - Main Component List for the First Prototype (see figure 7.3).**

| Part No. | Parts Description          | Material  | Appendix Ref. No. |
|----------|----------------------------|-----------|-------------------|
| 1        | 60 x 130 Flexator Actuator | Al. alloy | L.1               |
| 2        | Joint 2 Connector          | Al. alloy | L.2               |
| 3        | Potentiometer Mounting     | Al. alloy | /                 |
| 4        | Joint 3 Rear Mounting      | Al. alloy | /                 |
| 5        | 60 x 90 Flexator Actuator  | Al. alloy | L.3               |
| 6        | Joint 3 Front Mounting     | Al. alloy | /                 |
| 7        | Mode Change Bearing        | Brass     | /                 |
| 8        | Joint 4 Connector          | Al. alloy | L.4               |
| 9        | 60 x 170 Flexator Actuator | Al. alloy | L.5               |
| 10       | Connector Link 2           | Al. alloy | L.6               |
| 11       | Extension Tube End Cap     | Al. alloy | /                 |
| 12       | Joint 5 Front Mounting     | Al. alloy | /                 |

|    |                |           |   |
|----|----------------|-----------|---|
| 13 | Extension Tube | Al. alloy | / |
| 14 | Link 2 Tube    | Al. alloy | / |
| 15 | Link 1 Tube    | Al. alloy | / |

The estimated mass of the first prototype before manufacture was 5.6 kg not including the mass of the wrist/end effector. After manufacture, the mass of the whole arm was 7.9 kg, some 2.3 kg over the estimated design weight, and just under the max system weight as given in the final design specification, the reasons for this were due to the weight of the large brass bearing used in the mode change joint (1.6 kg), and the underestimated mass of the connecting links.

The final mass of the prototype was still considerably lighter than other purpose-built wheelchair-mounted systems, developed by earlier research groups (see Table 7.4).

**Table 7.4 - Overall Mass of Purpose-Built Wheelchair-Mounted Systems.**

| Research group                        | Main materials used      | Overall mass |
|---------------------------------------|--------------------------|--------------|
| V.A. Medical Center                   | Aluminium & Steel        | 20 kg        |
| Spar Aerospace/O.C.C.C                | Aluminium                | 23 kg        |
| Institute for Rehabilitation Research | Aluminium & Carbon fibre | 20 kg        |
| Middlesex University                  | Aluminium alloy          | 8 kg         |

Reducing the mass of the manipulator can have a great effect on its dynamic performance and safety, and must therefore always remain a primary design goal.

#### 7.4.4 Cable and Hose Routing on the First Prototype Arm

Ideally all electrical cabling and pneumatic hoses would pass through the centre of the rotary joints and through the arm structure. However, in reality it is not always possible to pass cables and hoses through the centre of joints. In the prototype design the actuator drive shafts were designed to be solid for maximum strength, and therefore a compromise had to be reached. The cables and hoses were guided externally around the rotary joints and then passed into the arm structure via cut-outs in the tube walls, emerging just before the following joint. Within links 1 & 2 the potentiometer and actuator mounts were machined to have a truncated cylindrical appearance to allow cables and hoses for the following joints, to run the length of the links. The first prototype arm had five pneumatic joints, requiring ten pneumatic hoses of  $\phi 4$  mm, as well as three potentiometers, which required nine electrical cables of  $\phi 1.5$  mm.

The requirement to pass cables and hoses was less, the further the distance travelled along the arm, until the last actuator, joint 5, was reached. The use of the two linear axes, joints 1 and 5 incurred some particular snagging problems which would be overcome in a production version of the prototype, by the use of:

- *A cable and hose enclosure which could roll on itself so allowing prismatic joint 1 to extend and retract without snagging, and*
- *Coiled cabling after joint 5, so that the cables required for the wrist/end effector could be extended and retracted without snagging.*

Future prototype designs would seek to utilise hollow drive shafts and even rotating connectors to pass cables and hoses straight through the centre of the arm.

#### 7.4.5 Selection of the Fluid Control Valves for the Pneumatic Joints

Having selected pneumatic actuators for the first five joints of the prototype arm, the next step was to decide upon the type of fluid control valves to be used to control these joints. The original electrical solenoid valves used in the Inventaid manipulator were fairly large, heavy and had a power rating of 2.5 W. After searching for alternatives to these valves, a source of smaller, lighter valves having a lower power rating was found. The valves chosen for the middlesex manipulator were the VJ100 series, 3 port miniature electrical solenoid valves from SMC Pneumatics (UK) Ltd. The advantages of these valves are given below:

- *Small width (only 10 mm);*
- *Lightweight (only 13 grams);*
- *Low power rating (only 1W);*
- *Low cost (£23.94+VAT);*
- *Large range of input voltages available (including 24Vdc);*
- *Large range of electrical connectors available;*
- *Fast response times (< 10 ms);*
- *Variable actuation types (normally closed or normally open);*
- *Two flowrates available from the standard valve (higher flow at lower pressure);*
- *Operating frequency range of 0 to 20 Hz;*
- *Manual override of the valve is possible;*
- *No lubrication required;*
- *Can be mounted in any orientation;*
- *Dust proof enclosure;*
- *Surge voltage suppression available;*
- *Impact/vibration resistance (15G/3G (8.3~2000 Hz), and*

- LED indication available.

The valve selected for the three flexator joints together with joint 5, was the VJ114-5MN type (normally closed, operating pressure 0-7 bar, 24Vdc with M type plug connector without leads). The prototype arm therefore used sixteen of this type of valve. Because joint 1 of the system had a larger flowrate requirement than the other joints, it was decided to use four VJ114A-5MN type valves (normally closed, operating pressure 0-4 bar, 24Vdc, M type plug connector without leads) for this joint. Although having a reduced operating pressure range, this type of valve does have a 50% larger effective orifice area and hence a larger flow rate.

7.4.5.1 Method of joint control using VJ114 valves

Each pneumatic joint in the prototype arm, whether linear or rotary, consists of two independent chambers, that shall be called 1 and 2. By controlling the mass flow rates into and out of these chambers control of the position of each joint can be obtained. Each pneumatic joint within the arm is controlled by the use of four solenoid valves (two inlet and two exhaust) mounted onto a manifold block. The manifold block has connections to the supply pressure line, both chambers of each actuator and an exhaust port. Figure 7.4 shows the layout of the valve assembly for a single joint. Internal tappings within the manifold block connect the valve orifices to the inlet/outlet ports together with either the supply or the exhaust ports (depending on the valve type, ie inlet or exhaust). Table 7.5 shows the logic arrangement to control a single joint in either direction.

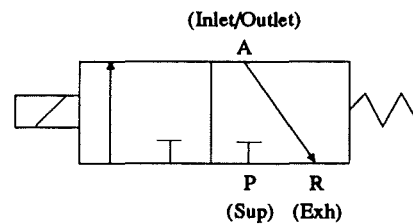


Figure 7.4 - VJ114 valve internal tappings.

Table 7.5 - Logic table for joint control.

| State   | Chamber 1 Port   | Chamber 2 Port   |
|---------|--|--|
| Cw/in   | Connected to the supply port via inlet valve 1 (exhaust valve 1 closed)  | Connected to the exhaust port via exhaust valve 2 (inlet valve 2 closed) |
| Ccw/out | Connected to the exhaust port via exhaust valve 1 (inlet valve 1 closed) | Connected to the supply port via inlet valve 2 (exhaust valve 2 closed)  |

PLAN VIEW

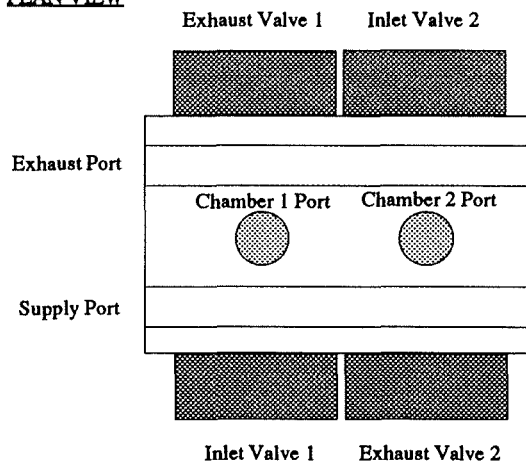


Figure 7.5 - Schematic of valve layout.

### 7.4.5.2 Pulse width modulation (p.w.m) of VJ114 valves

The decision in Section 7.4.5 to use simple on/off type solenoid valves instead of more sophisticated proportional type valves was based mainly on cost. Simple on/off solenoid valves cost approximately £25 each, whereas proportional valves of similar specification cost approximately £200+ each.

The VJ114 valves, used in the prototype arm are either on or off, and it is therefore not possible to gain proportional control over the movement of a joint using conventional methods. However, by pulsing the valve on and off many times per second, it is possible to obtain proportional control over a joint. Further it is possible to vary the mass flow rate of the valve by altering the mark to space ratio of the PWM signal (the ratio of the time that the valve is on, to the time that it is off). Figure 7.6 illustrates how the voltage pulses applied to the valve result in a mean flow rate output, due to the low pass filtering properties of the flexator..

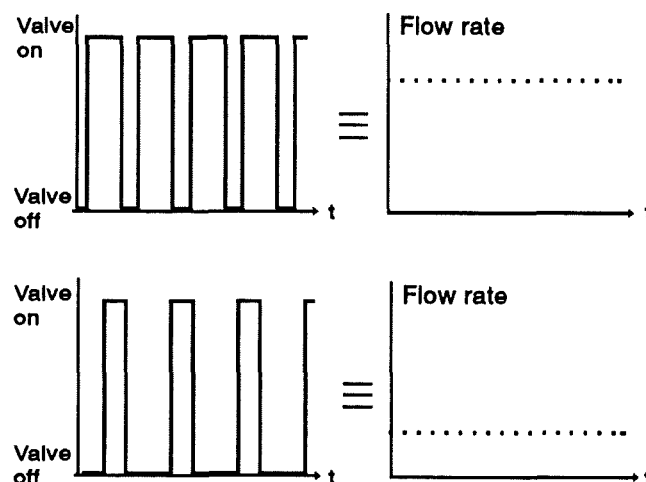


Figure 7.6 - Effect of mark to space ratio on valve flowrate

### 7.4.6 Control System Design (Prior, 1993b)

In contrast to some previous wheelchair-mounted projects, it was decided to use a microprocessor based control unit. Based on the authors design, illustrated in figure 7.7, the hardware and software for the controller was developed by a German placement student, Peter Oettinger. The advantages of having a microprocessor based controller can be summarized as follows:

- *The safety aspects can be increased by writing appropriate software routines;*
- *Often used position locations can be stored in memory and recalled when required;*
- *Joint positions can be monitored & controlled when the arm is not being driven by the user, ie to prevent movement due to leaks or payload slippage, etc;*



- *The pneumatic control valves can be operated using pulse width modulation;  
> enabling proportional control of the arm, and  
> the ability to vary the velocity of each joint;*
- *Ease of maintenance, because the components are mounted on a printed circuit board;*
- *Flexibility, because the software program can be changed without changing the hardware configuration, and*
- *Low cost, since the controller can be manufactured for under £150.*

The controller designed for the first prototype arm was based on a single processor system, which meant that only one control algorithm could be executed at a time. The system was operated sequentially and the different joints of the arm were controlled one after another. It would have been possible to use a multi-processor system for controlling the arm, so that every joint has a controller of its own. This system would have been faster, with several joints moving at the same time, but it would also have been much more expensive and more complicated to control. Since one of the main objectives of the project was to develop a low-cost system, this option was ruled out.

#### *7.4.6.1 System architecture*

Altogether, the system required twenty miniature solenoid valves to move the arm (four valves for each of the five pneumatic axes), and three stepper motors to operate the wrist/end effector. The controller must also read in the input signals from the user interface and the position feedback signals from the three main rotary joints. To make the system safer, interrupt signals and other feedback signals from locking devices, etc could also be read in by the controller if necessary (see figure 7.7).

The microcontroller chosen for this system was an INTEL 8051, which had 4 I/O-ports with 8 pins each to communicate with the outside world, giving a total of 32 pins. Because the system was sequential and had to input and output many signals it was decided to use multiplexers in the circuit, which allowed a reduction in the number of input and output pins used. With all the control functions and algorithms being executed by the controller, the system did not need to use any additional analogue circuitry for doing comparisons or other functions. The system therefore maintained flexibility and could be easily modified or improved by changing the software program written in the Assembler language. Because the whole system consisted of (digital) IC's it should be very easy to maintain and repair, which means that the user will not suffer from long maintenance/service downtime.

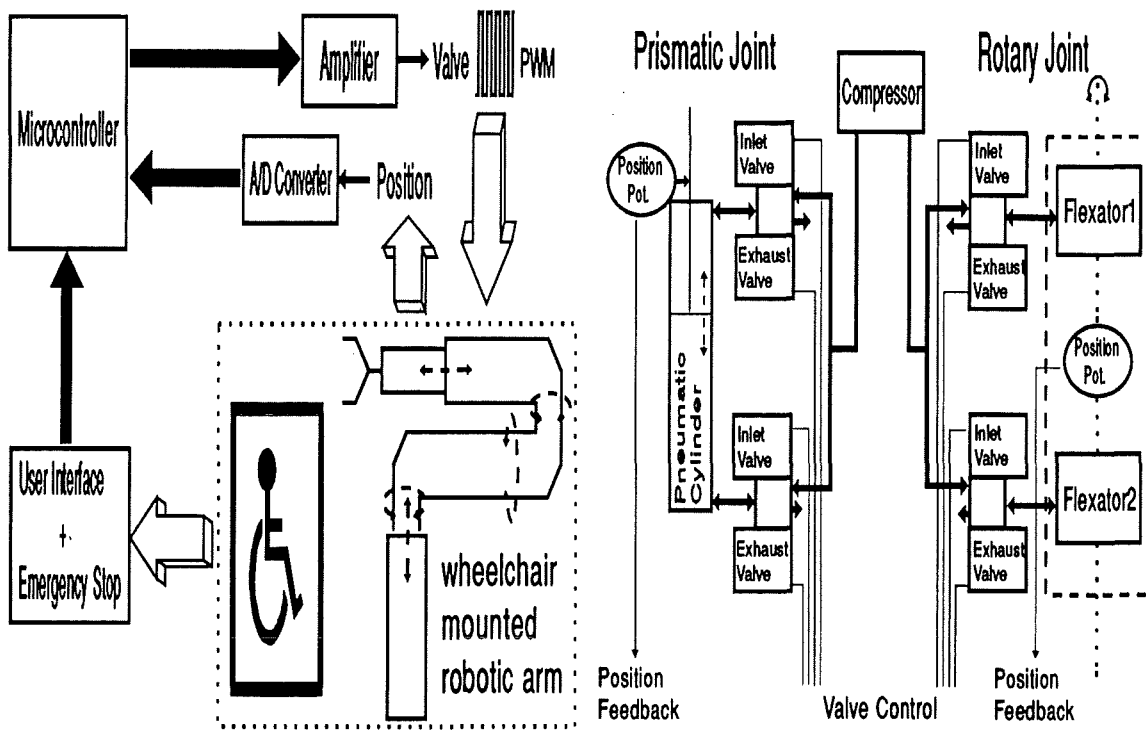


Figure 7.7 - Microprocessor controlled system configuration.

#### 7.4.7 Controller Hardware Description

The essential part of the control circuit is the INTEL 8051 microcontroller. It is used to control all the peripheral devices and enables the transfer of signals between the electronic and mechanical elements of the arm. Data comparisons for the position control will also be executed by the INTEL 8051, which allows for variation of precision (hysteresis band) of the system. Because all of the control functions are based on the software, the system is flexible and can easily be improved without changing the hardware. In the following section the parts that are used for the electronic control circuit are described.

##### 7.4.7.1 Microcontroller INTEL 8051

Port 1 is used to switch all the solenoid valves. Pin 1.0 - Pin 1.3 switch the inlet valves while Pin 1.4 - Pin 1.7 switch the outlet valves of the pneumatic actuators via two demultiplexers 74LS154. For every valve there is a special 4-bit combination which must be written to the port to switch the valve (see port description in Appendix N).

Pin 2.0 - Pin 2.3 of Port 2 output a 4-bit combination to the demultiplexer 74LS138 and the data selector 74LS151 which select one of the A/D converters. For every A/D converter there is a special 4-bit combination (0000B-0111B) which must be written to the port to select the A/D converter. The fourth bit (Pin 2.3) is always 0, because it is

also the /chip select signal for the dataselector. Pin 2.4 - Pin 2.7 of Port 2 are used to read in 4-bit combinations (16 possible keys) which represent the instructions from the operator to control the robotic arm. The 4-bit combinations can be generated by any digital user interface that is connected. The first system version uses a hex-keypad as an interface between the system and the operator.

Pin 3.0 and Pin 3.1 of Port 3 realize the data transfer for the position feedback. The data byte (LSB first) enters through Pin 3.0 (RXD - serial input port) which is sent from one of the A/D converters. Pin 3.1 (TXD - serial output port) outputs the shift clock which is necessary for the correct data transfer. The baud rate is fixed at 1/12 of the oscillator frequency. Pin 3.2 (/INT0 - external interrupt) is connected to the emergency switch and has the highest priority level of all input signals. Pin 3.3 (/INT1 - external interrupt) is connected to the 'data available' signal of the user interface (keypad).

The unused pins are wired to connector B so that they can be used for another purpose in later versions (see Appendix N for more details about the microcontroller INTEL 8051 and the port description).

#### 7.4.7.2 Quartz crystal 8MHz/12MHz

By connecting a quartz crystal to the pins XTAL1/2 the on-chip oscillator of the microcontroller is used (for correct connection, see Appendix N). Because of the great importance of the system response time a high frequency crystal was used.

#### 7.4.7.3 Power driver CA3242

The microcontroller cannot switch the valves directly because each solenoid valve requires a supply of 24V and 100mA. So the power driver CA3242 is connected to an amplifier between the controller and the valves. One IC consists of four power drivers so that five IC's must be used to switch the twenty solenoid valves on and off.

#### 7.4.7.4 A/D Converter TLC549IP

The TLC549IP is an 8-bit serial, analogue to digital converter. An A/D converter together with a potentiometer form the feedback unit for a joint. The converter reads in the voltage from the potentiometer and converts it into an 8-bit value. When the chip select signal is set by the controller and the shift clock reaches one, the converter outputs the data byte (MSB first), which is proportional to the position of the joint.

#### 7.4.7.5 Voltage regulator L78S05

The electric wheelchair is supplied by a 24V battery. The motors which drive the wheelchair and the solenoid valves need a supply voltage of 24V, but the digital control circuit only needs a 5V supply voltage. The voltage regulator which is being used transforms any voltage from 8 to 35V down to 5V.

#### 7.4.7.6 Datasector 74LS151

This selector can switch between 8 data lines which are connected to the A/D converters and outputs the selected line to the serial input of the controller. To select one of the 8 A/D converters a 3-bit combination (000-111) must be written to the datasector via Pin 2.0, 2.1 or 2.2. Pin 2.3 of the controller delivers the /chip select signal.

#### 7.4.7.7 Demultiplexer/Decoder 74LS138

This demultiplexer outputs the /chip select signals for several A/D converters, so that only one converter is selected at any one time.

#### 7.4.7.8 Demultiplexer/Decoder 74LS154

Two of these demultiplexers are used in the circuit. Each of them can decode between 16 outputs which are chosen by a 4-bit combination. One demultiplexer switches the inlet valves, whilst the other demultiplexer switches the exhaust valves of the pneumatic actuators. The unused outputs are wired to connector B. They may be used to control the stepper motors of the wrist/end effector. Because the demultiplexer works with negative logic and the amplifiers CA3242 with positive logic, inverters must be connected between these parts.

#### 7.4.7.9 Inverter 74LS04

Some signals (output from the demultiplexers 74LS154, interrupt signals, shift clock for the serial input, etc) have to be inverted so that the circuit can work correctly. In the chips used there are six integrated inverters.

#### 7.4.7.10 Potentiometer 10k $\Omega$

Rotary potentiometers are mounted on the three main rotary joints of the arm and are supplied by 5 Vdc. Each of them is connected to an A/D converter to which the

potentiometer delivers a voltage between 0 and 5 Vdc. This voltage is proportional to the angular position of the corresponding joint (0 to 340°).

#### *7.4.7.11 User interface*

The user interface is realized by 8 pins at connector A. Any user interface that generates a digital 4-bit combination and a 'data available' signal can be connected to the control unit. With a digital 4-bit combination 16 different user keys can be realized. One of these pins is an input for the emergency switch. The remaining two pins are the power supply (+5V and GND) for the interface. The first version of the system uses a hex-keypad (16 keys) as its user interface (for the correct connection of the user interface, see Appendix N).

Note: when the A/D converter outputs the data byte the most significant bit is sent first. But when the microcontroller reads in the data byte the least significant bit is received first. This must be considered when writing the software routine to input a feedback signal.

For realizing a correct handshake between the A/D converters and the microcontroller the shift clock must be inverted to correctly transmit the data bytes (see Appendix N).

#### **7.4.8 Production of the Printed Circuit Board**

After the electronic circuit was developed, the design of the printed circuit board was carried out. PCB manufacturing facilities were available at the University. The circuit was designed using the electronic CAD package EASYPC. Other more sophisticated software packages, such as ORCAD, were available but were not compatible with the manufacturing process. With EASYPC all the steps in the design have to be carried out manually, eg routing, control of the correct connections, etc, but it has the advantage that it is easy to use. After creating the layout of the PCB, the board was produced using the facilities already mentioned (see Appendix N).

#### **7.4.9 Controller Software Development (see Appendix P)**

The development of the controller software for the project was done in parallel with the hardware development, as far as this was possible. Close attention was paid to the various hardware issues that arose during the development phase. Software was written for the microcontroller in the Assembler language. A C-crosscompiler for the INTEL 8051 was also available, but was not used for the coding of the first prototype controller. Using Assembler had the advantage that the routines are normally shorter and more

efficient than other control languages. The length of the routines affects the speed of the system and is an important point because the control unit is a real-time system which should have short response times. It should be noted when developing the software, that the single processor system must control all the joints in a sequential way and the longer the written program, the longer will be the response time of the system.

#### 7.4.9.1 Software requirements (see figure 7.8)

The software requirements for the system follow directly from the hardware and functional requirements. The software requirements for the microcontroller based system consists of three main functions, with the following priority:

- *Emergency stop.*
- *Read user input and execute the command.*

*Operation mode:*

*.....move the arm joints under manual control.*

*.....move the arm to a pre-set function location.*

*Setup mode:*

*.....store a function location.*

*.....choose an operating speed.*

- *Control the stationary position of the arm (ie, no user input).*

The completed program consists in general of the following listed routines:

- *Initialisation of the system;*
- *Read the user input and select the chosen key;*
- *Switch on or off the inlet and corresponding exhaust valve of a flexator or a pneumatic cylinder, or give a control signal to a stepper motor to move a joint;*
- *Delay routines;*
- *Read from an A/D converter (serial input), and*
- *Compare the demand and actual position.*

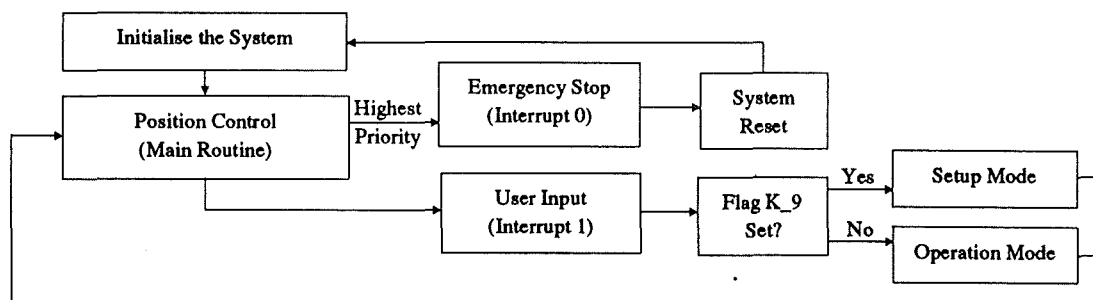


Figure 7.8 - Main control flow chart

## 7.4.10 Main Realised Functions

### 7.4.10.1 Emergency stop

Because of the safety aspects, the emergency stop function is realized as an interrupt routine with the highest priority. This means that if the emergency stop switch is pressed the controller stops the execution of the main program immediately and the program jumps to the interrupt routine. This is the only function to stop all other programme execution and to close all solenoid valves so that the arm can not be moved. To quit this routine the user has to reset the system via a system power-up. The safety aspects of this research are very important, especially when placing a robotic device so close to the human operator, who in this case does not possess the necessary reflex actions and/or strength to move out of the way should anything go wrong.

### 7.4.10.2 User input

This function is also realized as an interrupt routine, but with second priority. If the user makes an input, an interrupt signal is generated which causes the controller to jump to the corresponding routine. Firstly the controller reads in the input signal and then has to ascertain which key was chosen, to enable it to execute the corresponding function. If the user wants to move a joint manually, they execute the command cw/up by pressing key A or ccw/down by pressing key 0, the controller will execute the command until the key is no longer pressed. To move another joint, the user must choose the corresponding joint number key (1,2,...,5 for the arm or 6,7,8 for the end effector). Then the joint can be moved with the cw/up or ccw/down keys (see figure 7.9).

Note: The gripper was not installed on the first prototype version of the arm. This meant that keys 6, 7, and 8 were not used to select the end effector joints. For the purpose of testing and demonstration, the selected joints (keys 1-5) of the prototype can be moved without pulse width modulation, ie continuously on, by using key 7 for cw/up and key 8 for ccw/down. If the user wants to move the arm automatically to one of the function locations, he chooses the corresponding key (B, C, D, E or F). The microcontroller reads in the actual positions of the main joints via position feedback and compares them with the corresponding function locations. Then every joint will be moved towards the function location until the actual, and the function location are equal.

The functions described above belong to the 'operation mode'. Using the 'set key' number 9 (#9H) the mode can be changed to the 'setup mode'. In this mode the user has the possibility to choose between three operation speeds (keys 1, 2 or 3) or to store four of the five available function locations (keys C, D, E or F). The home or park position of

the arm (key B) cannot be changed by the user, because this location is a fixed position. After choosing the set key 9 in conjunction with any other key, the system will return to the operation mode. Choosing the set key 9 twice cancels the setup mode and the system will return to the operation mode without having changed anything in the setup mode.

#### 7.4.10.3 Position control

After the last user input, the system reads in the location of the arm and stores it in a temporary memory. This value is the nominal location until the user produces an new input. The system works in a loop, it reads in the actual location of the arm and compares it with the nominal location. If there is a difference between those values, the arm will be moved until both locations are equal. Again it reads in the actual location. This function ensures that in the event of a removal of the external load or leakage of a flexator, the feedback signal will endeavour to maintain the desired position of the arm. The control routine of a rest position will be immediately interrupted by any user input.

#### 7.4.11 Human Robot Interface (H.R.I.)

As discussed in Section 2.3, there are many different types of user interface available today to allow people with special needs to control their environment (Gunderson, 1985). A selection of some of these devices is given below:

- *Push button type switches;*
- *Wobble sticks;*
- *Joysticks;*
- *Wrinkle switches;*
- *Sip/Puff switches;*
- *Light beam switches;*
- *LED pointers;*
- *Electromyographic (E.M.G) sensors;*
- *Electrooculographic (E.O.G) sensors;*
- *Infrared eye reflection devices, and*
- *Speech recognition systems.*

The above list was by no means exhaustive, and is being added to all the time. One of the most important new developments in the area of user interface research is the tongue controller being developed by Hennequin for the inventaid manipulator (see Section 2.3.7.3).

Faced with such a daunting selection of user inputs, it was decided to utilise a tried and tested technology, one that was readily available at a low cost, and had the ability to be



easily programmed. The type of interface chosen for the prototype arm was a 16 key hex-keypad. The keypad interface to the controller was designed to be modular, so that any similar device could be quickly and easily interfaced to the arm.

7.4.11.1 Functional description of the keypad interface

Operation mode:

1/2/3/4/5/6/7/8 + A/0 - Move the selected joint cw/up or ccw/down.

- Key: 1 - Arm (up/down) (prismatic)  
 2 - Shoulder ( $\pm$ ) (rotary)  
 3 - Mode change ( $\pm$ ) (rotary)  
 4 - Elbow ( $\pm$ ) (rotary)  
 5 - Wrist/End effector (in/out) (prismatic)  
 6 - Wrist roll ( $\pm$ ) (rotary)  
 7 - Wrist yaw ( $\pm$ ) (rotary)  
 8 - End effector open/close (prismatic)  
 A - cw/up  
 0 - ccw/down

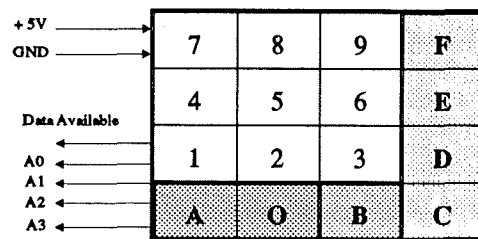


Figure 7.9 - Keypad layout and I/O channels

B/C/D/E/F - Move the arm automatically to the defined function location.

Table 7.6 - Truth Table of the Keypad Output.

| Key  | / | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | A | B | C | D | E | F |
|------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D.A. | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| A3   | X | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| A2   | X | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| A1   | X | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| A0   | X | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |

Setup mode:

- 9 ----- Change from the operation mode to the setup mode.  
 9 + 9 ----- Return to the operation mode without any modification in the setup mode.  
 9 + 1/2/3 ---- Choose the joint speed (1=fast, 3=slow) and go back to the operation mode.  
 9 + C/D/E/F Store the current joint positions as a memory location for the corresponding function key (C, D, E or F).

## 7.5 MANIFOLD DESIGN AND CONSTRUCTION

The pneumatic manifold for the prototype arm is a critical component in the overall system configuration. This device enables the operating medium (air pressure) to be directed to or from the two control chambers of each pneumatic actuator. In Section 7.4.5.1 the method of joint control using VJ114 solenoid valves was briefly described; the design of the manifold is discussed here in more detail.

The original manifold design utilising the three port VJ114 type solenoid valve was developed by Hennequin for use on the Inventaid manipulator. The design consisted of an Aluminium alloy block which was drilled and tapped to produce the supply and exhaust galleries, the ports to the control chambers of each actuator, and the internal passages which connect up to the solenoid valves (see figure 7.10). The VJ114 type solenoid valve has three internal ports. P is the supply port, R is the exhaust port and A is the bi-directional inlet/outlet port (see figures 7.4 and 7.10). In the prototype system, each pneumatic joint has three independent states:

- *Moving clockwise/up;*
- *Moving counterclockwise/down, or*
- *Stationary.*

So although each solenoid valve has three ports, only ports P and A are used. The third port, R is effectively blocked off. When none of the solenoid valves are activated, the pressure inside the chamber is maintained, due to the fact that ports P are closed and port

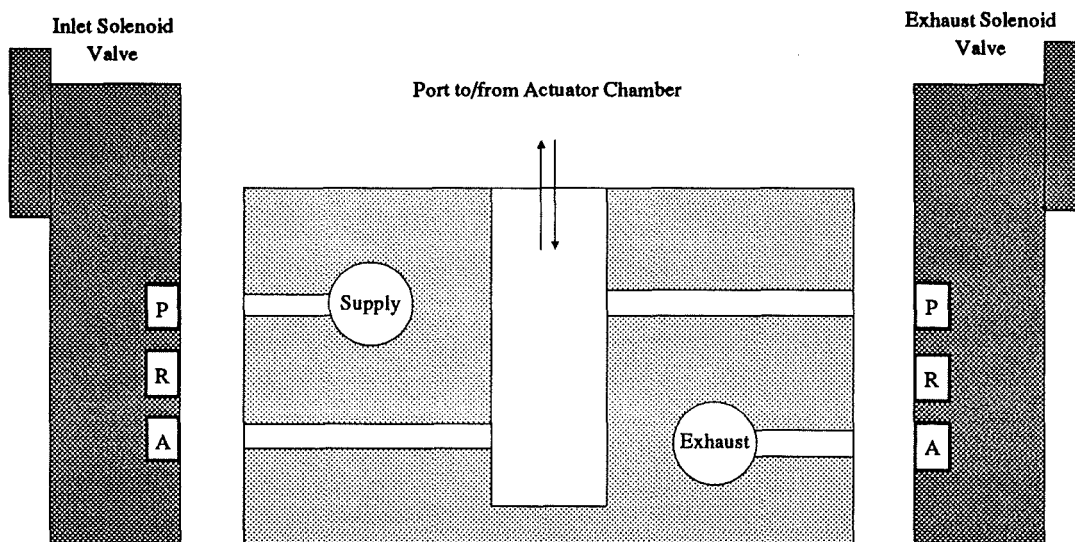


Figure 7.10 - Sectional view of manifold block & valves.

A on the valves are connected to port R. To pressurize the chamber, only the inlet valve will be activated, allowing the supply gallery to be connected to the chamber via port A. To exhaust the chamber, only the exhaust valve is activated, thus allowing the chamber pressure to be connected to the exhaust gallery via port A.

Since there are two chambers per joint, it is possible to control the position of each of the five pneumatic joint's using twenty 3 port solenoid valves. Joint 1, the vertical arm lift actuator, required a much larger flow rate of air than the other joint actuators to enable it to match the linear velocity specification, it was decided therefore to use four VJ114A type valves for this particular joint (50% larger effective orifice area). However, since these valves only operate up to 4 bar, this meant that a separate manifold was required, together with a pressure regulator. A working drawing of the main manifold block (for sixteen VJ114 valves operating at 6 bar) appears in Appendix Q. The original manifold has been redesigned to be as compact as possible, the size being only 96.5 x 25 x 15.25 mm. The manifold was modelled using the 'IDEAS' CAD package from SDRC, and a shaded image of the manifold is shown in figure 7.11. The following section provides details of the theoretical flow rate modelling and experimental measurement of the VJ100 series valves used in the prototype system.

## 7.6 FLOW RATE ANALYSIS OF THE VJ114 SOLENOID VALVE

The flow rate of a control valve is of primary importance, since it is this quantity that determines the speed of a particular actuator. The performance of a fluid control valve is defined by industry standard flow coefficients, such as  $C_v$ ,  $K_v$  and  $S$ .

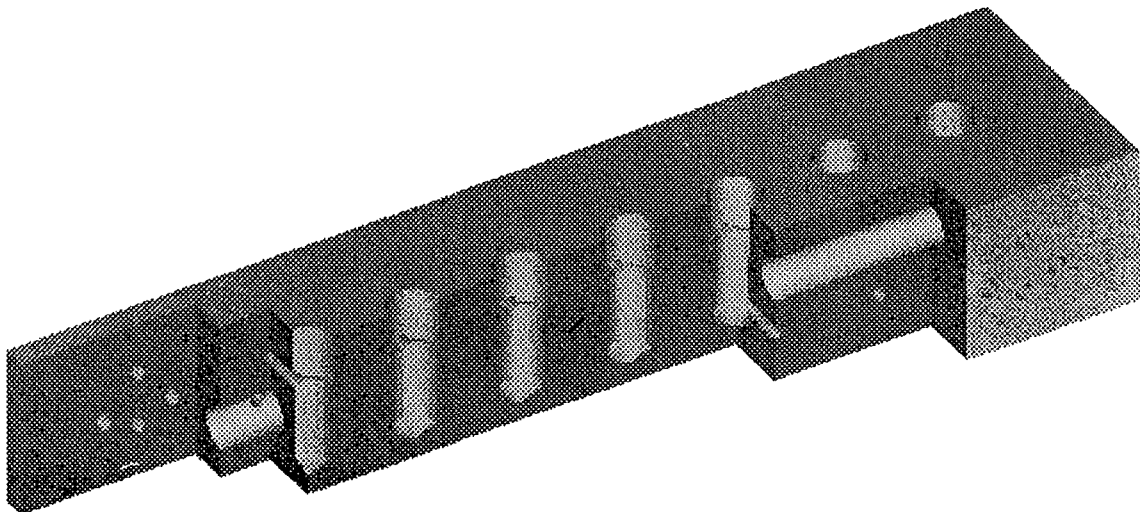


Figure 7.11 - Shaded image of manifold designed using IDEAS.

A  $C_v$  of one is equal to a flow rate of one US gallon of water per minute, with a pressure drop of one psi. A  $K_v$  of one is equal to a flow rate of one litre of water per minute, with a pressure drop of one bar. The label  $S$  refers to the effective cross-sectional area in  $\text{mm}^2$  of the orifice in a control valve. Manufacturers of fluid control valves will typically specify one or more of these variables in the product specification. Table 7.7 shows how these flow coefficients vary (SMC Pneumatics UK Ltd).

Table 7.7 - Conversion Between Flow Coefficients.

| $C_v$<br>(no units) | $K_v$<br>(ln/min) | $S$<br>( $\text{mm}^2$ ) |
|---------------------|-------------------|--------------------------|
| 1                   | 14.3              | 18                       |
| 1.2                 | 17.1              | 21.6                     |
| 1.17                | 16.7              | 21                       |
| 0.07                | 1                 | 1.26                     |
| 0.0556              | 0.793             | 1                        |

Table 7.8 below shows the flow coefficients for the VJ114 series solenoid valves manufactured by SMC.

Table 7.8 - Flow Coefficients for the VJ114 Series Solenoid Valves.

| Model  | Operating Pressure<br>(bar) | $C_v$ | $S$<br>( $\text{mm}^2$ ) |
|--------|-----------------------------|-------|--------------------------|
| VJ114  | 0-7                         | 0.008 | 0.14                     |
| VJ114A | 0-4                         | 0.012 | 0.22                     |

From the flow coefficient data shown in the table above it is clear that the VJ114 series valves represent one of the smallest flow control valves available on the market. The industry standard formula for calculating the air flow rate of a valve, under given conditions of pressure and using the  $C_v$  coefficient follows:

$$Q = 400 \cdot C_v \cdot \sqrt{((P_2 + 1.01325) \cdot \Delta P)} \cdot \sqrt{\left(\frac{273}{(273 + n)}\right)} \quad (7.3)$$

Where  $Q$  is the standard flow rate of the valve in ln/min,  $C_v$  is the coefficient of flow,  $P_2$  is the outlet pressure required (bar gauge),  $\Delta P$  is the permissible pressure drop (bar), and  $n$  is the air temperature in °C. At normal working temperatures the final part of the equation approaches one and therefore can usually be neglected.

The above formula is only valid for a system with a small pressure drop of up to one bar. If the pressure drop in the system exceeds about one bar, then the flow in the system is probably turbulent, and the above equation cannot be applied. Fluid flow in a pneumatic system can occur in one of two forms, laminar or turbulent:

- *Laminar flow* - where the pressure loss in a given length is proportional to the flow rate, ie  $\Delta P \propto Q$  (Reynolds number < 1200).
- *Transition region* - transition between laminar and turbulent flow (1200~2500).
- *Turbulent flow* - Where the pressure loss in a given length is proportional to the square of the flow rate, ie  $\Delta P \propto Q^2$  (Reynolds number > 2500).

Due to the complexity of modern miniature fluid control valves, the fluid can quickly become turbulent, adding to the complexity of the system's flow analysis.

### 7.6.1 Experimental Measurement of Flow Rate

The two types of fluid control valve, VJ114 and VJ114A, used in the prototype system were tested to measure their fluid flow characteristics. The experimental set up consisted of a 0-7 bar pressure supply, two (0-7 bar) 'Druck' pressure transducers connected to digital meters, a 'Honeywell' (0-20 SLPM) microbridge mass airflow sensor and a throttle valve (see figure 7.12).

The two types of valve were tested separately due to their different maximum operating pressure limits. The tests consisted of connecting the components together as shown in figure 7.12, the supply pressure was set to 6 bar (4 bar for the VJ114A valve) and the valve was energised using a 24 Vdc supply. The air pressure before and after the valve was measured together with the flowrate. The throttle was used to reduce the pressure drop across the valve to zero, in one bar intervals, taking measurements at each stage.

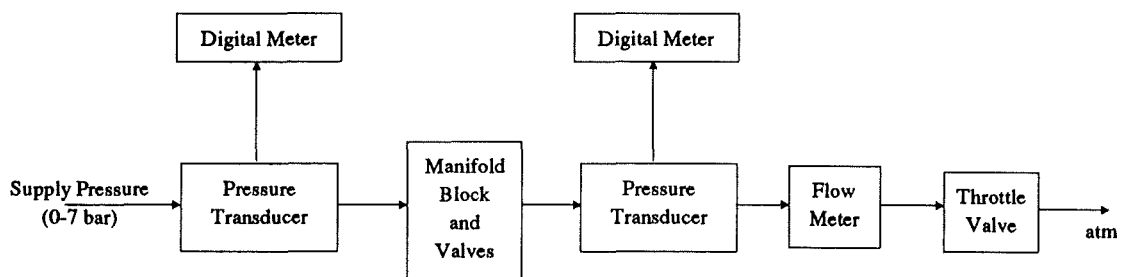
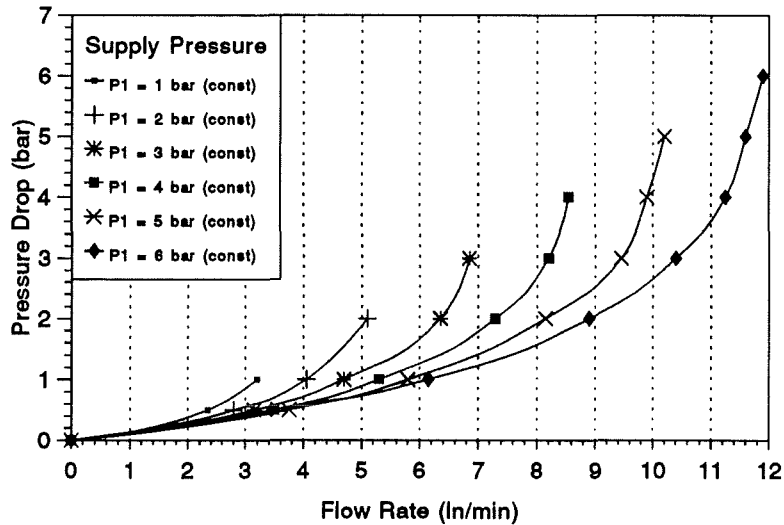


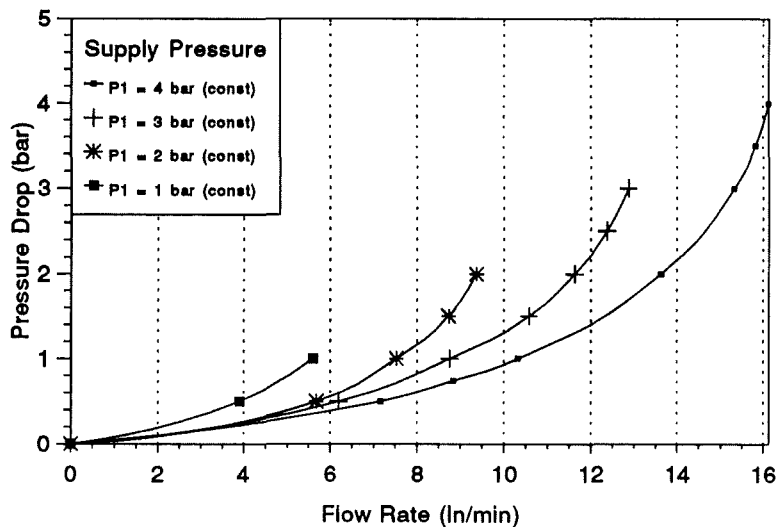
Figure 7.12 - Experimental measurement of valve flow rates.

The supply pressure was then reduced by one bar and the complete test repeated. The results of these tests showed that when operated at a pressure drop of more than one bar, both valves were experiencing turbulent flow regimes (see figures 7.13 and 7.14).



Cv = 0.008

Figure 7.13 - Flow rate test of VJ114 solenoid valve.



Cv = 0.012

Figure 7.14 - Flow rate test of VJ114A solenoid valve.

### 7.6.2 Mathematical Modelling of Mass Flow Rates

To enable accurate modelling of pneumatic control valves, knowledge is required of the mass flow rates, related to the flow through the restrictions of the valve and manifold assembly.

Previous work (Czarnecki et al, 1988; French & Cox, 1990; Pu et al, 1993) has treated fluid power valves as simple nozzles, and applied one-dimensional compressible flow theory to determine their mass flow rate characteristics. However, the complex internal nature of modern miniature fluid valves and manifolds tends to reduce the critical pressure ratio for air from 0.528 to as low as 0.2 or lower, the rationale behind this was first established by PERA (Purdue et al, 1969) who used a value of 0.3. Further work by Sanville in 1971, proposed empirically based equations to account for the above effects, together with non-linearities caused by turbulent flow.

Another approach (Drazan & Thomas, 1978; Drazan, 1983) was to obtain the flow characteristics totally empirically. In this method a record was made of a constant volume pressure trace of an actuator chamber following a step signal to a solenoid valve. The assumption being, that the mass flow rate passing into or out of the actuator chamber is dependent only on the end pressures. Therefore since the supply and atmospheric pressures can be considered constant, the mass flow rate is a function only of the chamber pressure. By using the perfect gas equation and differentiating the polynomial series of chamber pressure with respect to time, the mass flow rate characteristics were obtained.

In this analysis both the above methods have been utilised and the results compared using a PC based 'Lotus' spreadsheet package.

From one-dimensional compressible flow theory, taking chamber 1 to be charging and chamber 2 to be venting, the following model applies:

$$\dot{m}_1 = \frac{K A_1 P_s}{T_s^{1/2}} \left[ 1 - \left( \frac{P_1/P_s - b_1}{1 - b_1} \right)^2 \right]^{1/2} \quad \text{for, } \frac{P_1}{P_s} > b_1 \quad (7.4)$$

$$\dot{m}_1 = \frac{K A_1 P_s}{T_s^{1/2}} \quad \text{for, } \frac{P_1}{P_s} \leq b_1 \quad (7.5)$$

$$\dot{m}_2 = \frac{K A_2 P_a}{T_a^{1/2}} \left[ 1 - \left( \frac{P_a/P_2 - b_2}{1 - b_2} \right)^2 \right]^{1/2} \quad \text{for, } \frac{P_a}{P_2} > b_2 \quad (7.6)$$

$$\dot{m}_2 = \frac{K A_2 P_a}{T_a^{1/2}} \quad \text{for, } \frac{P_a}{P_2} \leq b_2 \quad (7.7)$$

Where:

$A_1$  and  $A_2$  = the effective orifice area for charging and venting (0.14 or 0.22 mm<sup>2</sup>);

$b_1$  and  $b_2$  = the critical pressure ratios for charging and venting;

$\dot{m}_1$  and  $\dot{m}_2$  = the mass flow rates for charging and venting (kg/s) ;

$T$  = the absolute air temperature (K);

$P_s$  = the absolute supply pressure (N/m<sup>2</sup>);

$P_a$  = the atmospheric pressure (N/m<sup>2</sup>);

$P_1$  and  $P_2$  = the absolute chamber pressures when charging and venting (N/m<sup>2</sup>);

$\gamma$  = the ratio of specific heats (for air, 1.4);

$R$  = the specific gas constant (287 J/kg K);

$$K = \left[ \frac{\gamma}{R} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}} \quad (7.8)$$

$$K = 0.040418$$

Assuming standard ambient conditions, the only unknown variables in equations 7.4 to 7.7 are  $b_1$  and  $b_2$ . As a first approximation these can be taken as being equal to 0.528, the critical pressure ratio for a perfect nozzle.

$$\frac{P_c}{P_o} = \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma-1}} = 0.528 \quad (7.9)$$

Where  $P_c$  is the critical pressure and  $P_o$  is the stagnation pressure.

The significance of the critical pressure ratio lies in the fact that at this point, the flow velocity reaches the speed of sound  $u = \sqrt{\gamma R T} = 340 \text{ m/s}$ , for air at S.T.P. At this point the maximum mass flow rate of a nozzle is a function only of the stagnation conditions and the minimum cross-sectional area  $A_{min}$ . No matter how much the downstream pressure falls, the mass flow rate cannot be exceeded. Under these conditions the flow is said to be *choked* (see equation 7.10).

$$\dot{m}_{max} = A_{min} \left[ P_o \rho_o \gamma \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}} \quad (7.10)$$

$$\dot{m}_{max} = 2.308E-04 \text{ kg/sec (for the VJ114 valve, operating at 7 bar abs)}$$



The values of the critical pressure ratios,  $b_1$  and  $b_2$ , for charging and venting were obtained empirically, and were then used in equations 7.4 through to 7.7 to obtain the mass flow rate characteristics of the actuator under any given conditions of pressure. These flow characteristics will be shown to be more accurate than using either equation 7.3 or the theoretical mass flow rate equations 7.4 to 7.7, with a critical pressure ratio of 0.528.

### 7.6.3 Empirical Analysis of the Critical Pressure Ratios, $b_1$ and $b_2$

To measure the critical pressure ratios,  $b_1$  and  $b_2$  for charging and venting, a 60 x 90 dual flexator actuator was used. The actuator was instrumented with two pressure transducers, a mass airflow sensor and a potentiometer. The flexators were driven by VJ114 solenoid valves connected via a simple switching mechanism which enabled control of bi-directional movement of the actuator as well as a stationary position. The instrumentation was connected to a data acquisition system and readings were taken at 40ms intervals for charging and venting of the flexators (approximately 264 points). The raw data was then imported into a 'Lotus' spreadsheet, where data conversion and processing took place.

Using the perfect gas equation:

$$P_1 V_1 = M_1 R T_1 \quad (7.11)$$

$$P_2 V_2 = M_2 R T_2 \quad (7.12)$$

Rearranging 7.11 and 7.12 gives:

$$M_1 = \frac{P_1 V_1}{R T_1} \quad (7.13)$$

$$M_2 = \frac{P_2 V_2}{R T_2} \quad (7.14)$$

Differentiating the gas equation with respect to both the pressure and volume gives:

$$\frac{dm_i}{dt} = \left( P_i \frac{dv_i}{dt} + V_i \frac{dp_i}{dt} \right) \frac{1}{RT_i} \quad (7.15)$$

The raw chamber pressure data,  $P_1$  and  $P_2$  was converted into absolute pressure (Pa); the flowrate in terms of a voltage was converted to l/sec, and then the cumulative volume,  $V$

(m<sup>3</sup>) of each chamber was calculated. Equation 7.15 was then used to calculate the mass flow rates of chamber 1 (charging) and chamber 2 (venting). Equations 7.4 to 7.7, were also used to calculate theoretical values of mass flow rate for critical pressure ratios of 0.528, 0.2 and 0.15. A comparison between the theoretical and empirical data for charging and venting is shown in figures 7.15 and 7.16.

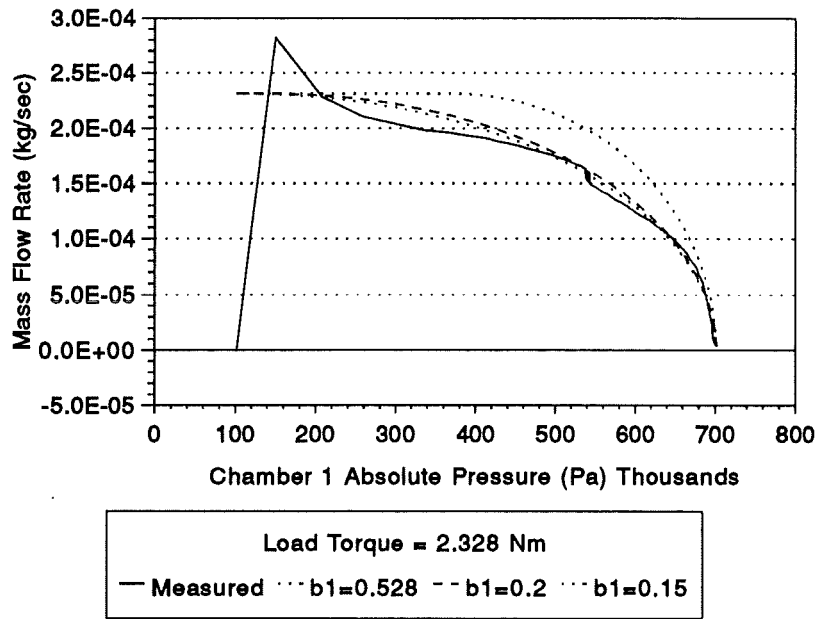


Figure 7.15 - Mass flow rate analysis: Chamber 1 charging.

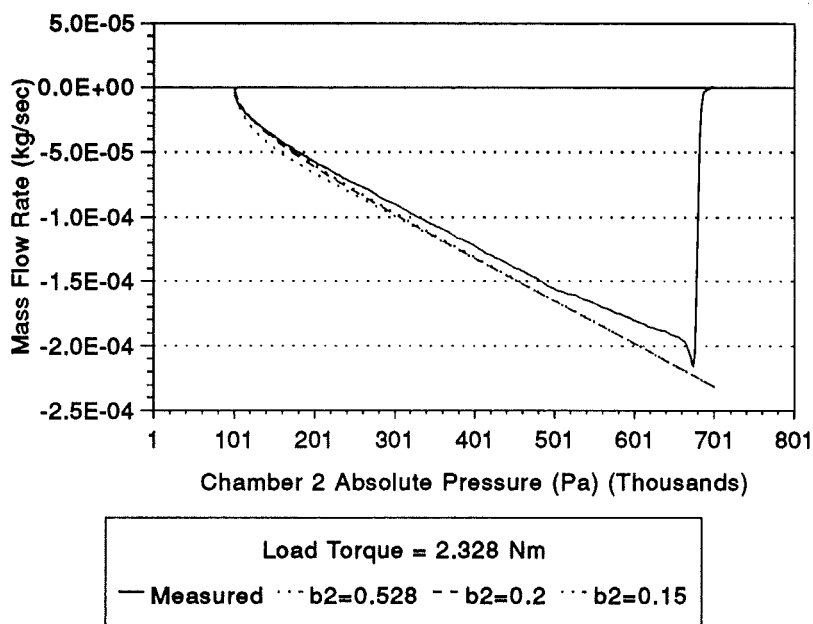


Figure 7.16 - Mass flow rate analysis: Chamber 2 venting.

#### 7.6.4 Results of the Mass Flow Rate Analysis

Figures 7.15 and 7.16 clearly show that the mathematical model of the mass flow rate matches very closely the empirical data and therefore these equations can be used to model any of the manipulators pneumatic actuators.

The empirical analysis of the critical pressure ratios for charging and venting shows that this ratio is suppressed more during charging than venting. Table 7.9 shows how the value of the critical pressure ratio affects the accuracy of the mass modelling.

**Table 7.9 - Effect on the Modelling Accuracy of the Critical Pressure Ratios.**

| <b>Chamber 1 Charging (Total Mass = 0.698E-03 kg)</b> |                                 |                |
|---|---------------------------------|----------------|
| <b>Critical Pressure Ratio, <math>b_1</math></b>      | <b>Total Modelled Mass (kg)</b> | <b>% Error</b> |
| 0.528   | 0.908E-03                       | +30.08         |
| 0.200   | 0.735E-03                       | +5.30          |
| 0.150   | 0.716E-03                       | +2.58          |
| <b>Chamber 2 Venting (Total Mass = 0.690E-03 kg)</b>  |                                 |                |
| <b>Critical Pressure Ratio, <math>b_2</math></b>      | <b>Total Modelled Mass (kg)</b> | <b>% Error</b> |
| 0.528   | 0.749E-03                       | +8.55          |
| 0.200   | 0.730E-03                       | +5.80          |
| 0.150   | 0.725E-03                       | +5.07          |

Therefore for accurate modelling of the mass flow rate the lowest value of the critical pressure ratio,  $b_1$  and  $b_2 = 0.150$  should be used. This simple yet powerful modelling technique can be applied to any fluid valve/manifold/actuator combination. Once accurate modelling for a particular actuator and load combination has been achieved, this can be incorporated into the overall manipulator control algorithm.

The use of a 'Lotus' spreadsheet enabled several other analyses to be carried out at the same time, ie the velocity of the air in the tubing ( $\phi$  2.5mm), the total energy input and output of the system and hence the efficiency of the flexator actuators (see figure 5.16). The air velocity analysis showed that when chamber 1 was charging, the max instantaneous velocity reached 38 m/s. Taking the air temperature as 293 K, this gives a Reynolds number of:

$$Re = \frac{ud}{\nu} = \left( \frac{38 \times 2.5E-03}{1.38E-05} \right) = 6884 \text{ (Turbulent flow)} \quad (7.16)$$

## 7.7 TESTING OF THE FIRST PROTOTYPE ARM

The prototype arm as detailed in Section 7.4 was connected up to the robot controller and the pneumatic valve/manifold system. Each component within the overall design was tested to see if they operated according to the design specification. This involved testing the directional control of individual joints, joint speed control, record and playback features as well as joint positional control and the emergency stop function. After elimination of minor problems caused by poor connections, leaks, etc, the system was tested and found to be fully functional. However, after initial trials it was clear that several of the joints had problems which could only be overcome by a redesign phase and the manufacture of a second prototype. This situation although undesirable was expected and therefore once the problems and their causes had been established, the redesign stage started almost immediately. The main problems of the first prototype arm are summarised below:

- *The shaft of the double-acting cylinder (joint 1) tended to bend under the high bending moment of the arm when the joint was at maximum extension and the arm was at maximum reach. The cylinder's piston seal tended to exhibit stick-slip when the arm was lowered, again caused by the large bending moment.*
- *Due to the large inertia of the arm, coupled with a on-off type of control algorithm, joint 2 tended to oscillate about a stored position when disturbed from this position by an external force.*
- *The 60 x 90 dual flexator actuator of joint 3 did not have enough room within link 1 to fully expand and therefore could not produce sufficient torque to successfully operate the mode change function.*
- *The flexators used in the 60 x 170 actuator of joint 4 were so long that they caused problems of friction of the webbing strap against the outer tube of the actuator. The ratio of their width to length meant that under large movement they tended to pop out from under the webbing strap, causing failure of the joint and potential danger to the user. The length and position of this actuator meant that the arm would have problems passing over a horizontal surface without interference.*
- *The telescopic design of joint 5 meant that the friction between the two Aluminium tubes caused stick-slip to occur. This was recognised at the design stage and could be overcome by either lightly oiling the bore or incorporating a PTFE sleeve.*

Overall the system performed well, however, the reach of the arm was considered too long, and the inertia of the arm was too high, if lowered, the dynamic performance of the arm could be improved. Although the above problems might seem excessive, it must be borne in mind that this was an experimental system incorporating a number of novel actuators and features, whose performance could not be accurately predicted before the

manufacturing stage. However, before the redesign stage began, small modifications to the original design were made, these consisted of machining cut-outs in link 1 so that the flexators could expand normally and using long tack glue to attach the webbing straps to the surface of the flexators. Both these modifications improved the performance of the system, but could not make up for the problems inherent in the original design. Figure 7.17 shows the oscillatory nature of joint 2 under different supply pressures (arm inertia  $2.443 \text{ kg m}^2$ ).

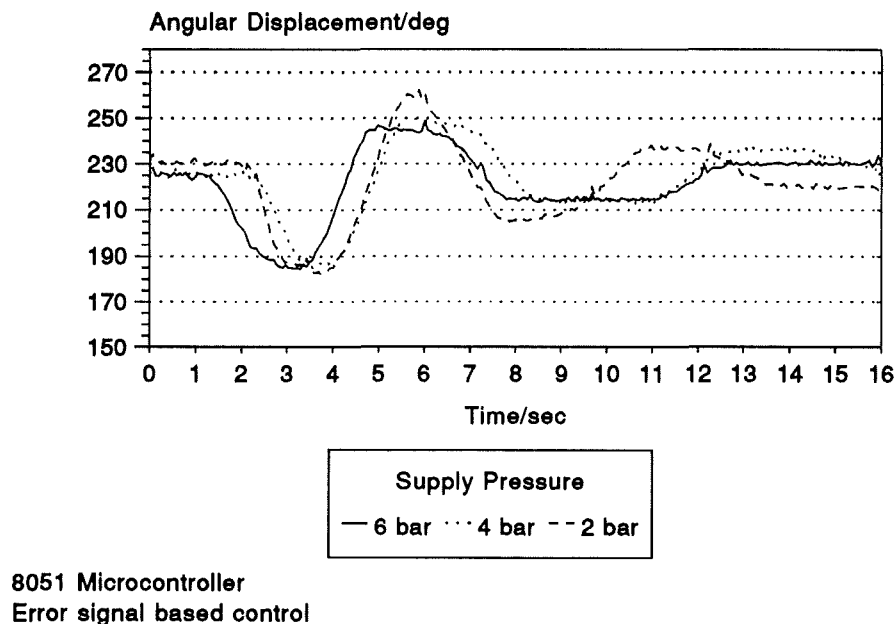


Figure 7.17 - Oscillatory nature of joint 2.

Investigations into the performance of the first prototype found that part of the problem of oscillation was due to the fact that the type of control implemented in the Assembly program was not a true pulse width modulated signal. Therefore, further research was conducted into the performance of the VJ114 type valves using a true PWM controller.

## 7.8 INVESTIGATIONS INTO THE PERFORMANCE OF THE VJ114 VALVE USING PWM

Analysis of the 8051 controller and Assembly program showed that rather than a proportional PWM controller, an on/off type of control was obtained which had three speed settings of which two were the same. Speeds 1 and 2 had a PWM frequency of 62.5 Hz with an equal mark to space time of 8 ms. Speed 3 was the slow speed and had a PWM frequency of 12.2 Hz, with a mark time of 8 ms and a space time of 74 ms.

The system therefore consisted of fixed frequency PWM system which could be changed manually by the user between 12.2 and 62.5 Hz, ie PFM (varying the space

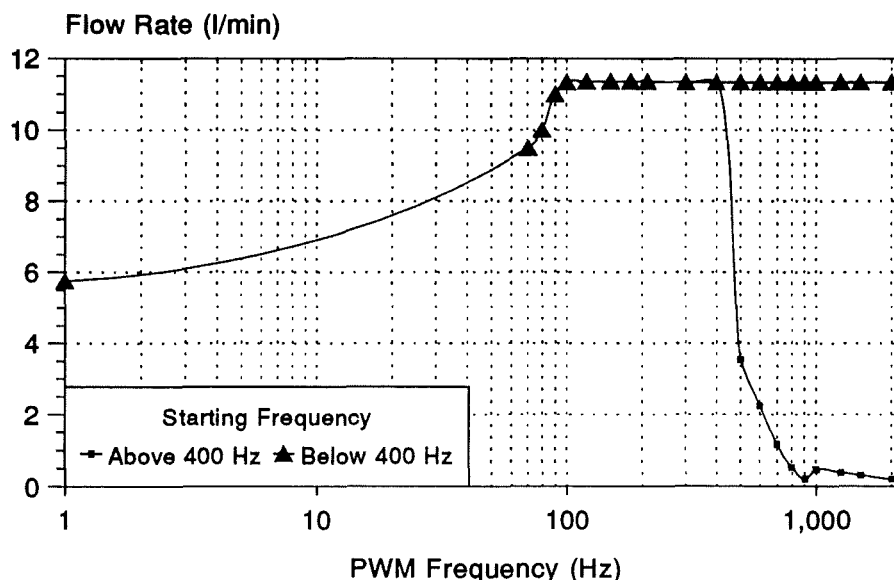
time from 8 to 74 ms). Manufacturers specifications for the VJ114 series valve, quoted a response time of less than 10 ms and a maximum operating frequency of 20 Hz.

A commercial PWM generator was connected to the VJ114 valves and tests were conducted into the valve's performance. In parallel with this work a request was made to SMC Pneumatics (UK) Ltd for some detailed information regarding the VJ114 valves construction and frequency response. However, after several conversations with SMC they would not release this information to the author. Therefore, all the basic testing of the valves using PWM signals had to be conducted at Middlesex.

### 7.8.1 Effect on the Flow Rate of Varying the PWM Frequency

The VJ114 valve and manifold system was used to test the effect on the flow rate of varying the PWM frequency of the valve, whilst keeping the mark to space ratio constant at 1:1. The PWM and flow rate signals were read on an oscilloscope and plotted out to paper. The PWM frequency was varied between 1, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100 Hz and over (see figure 7.18).

The flow rate was increased steadily, showing an increasing lag behind the PWM signal, as the frequency increased. The flow rate reached a maximum at approximately 100 Hz. The flow increased from 5.75 l/min at 1 Hz up to a max flow of 11.25 l/min at 100 Hz. Tests showed that when the valve was operated at a frequency of > 400 Hz the valve's



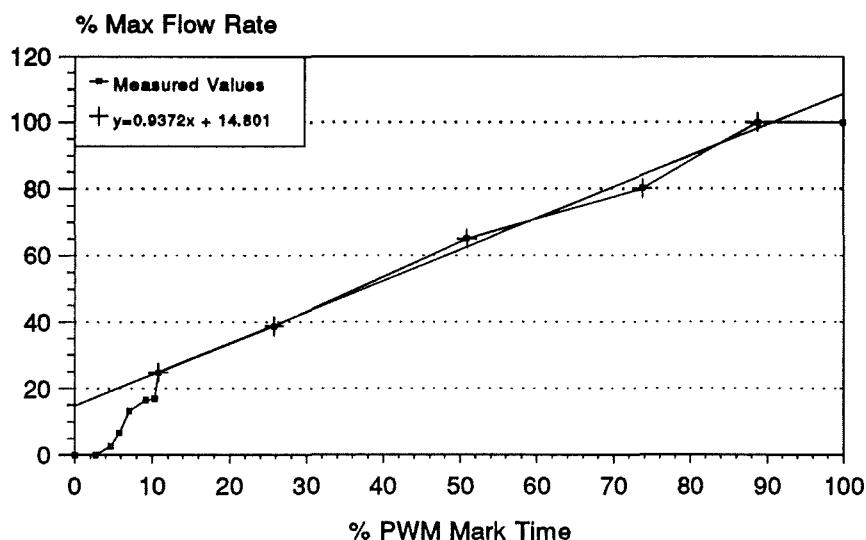
Pressure drop = 6 bar  
Natural Frequency @ 85 Hz

Figure 7.18 - Effect on the VJ114 valve's flow rate of varying the PWM frequency.

flow rate could be modulated by increasing or decreasing its frequency, however, when the valve's frequency was reduced to the 400 Hz point, the flow rate would suddenly jump to the maximum flow rate condition. Once this condition was reached, changing the frequency up or down had no effect on the flow rate. This phenomenon can be attributed to the non-linear features of the miniature solenoid which controls the position of the poppet valve shuttle.

### 7.8.2 Effect on the Flow Rate of Varying the PWM Mark to Space Ratio

As stated previously SMC Pneumatics quoted a maximum operating frequency of 20 Hz for their VJ100 series solenoid valves. It was unclear why this was a limiting factor, since from Section 7.8.1 it was known that the valves could be operated at up to 100 Hz. To date no relevant information has been obtained from SMC regarding the reason for this limiting figure, part of the reason could relate to the valves response time of 10 ms. Tests on a VJ114 valve were conducted at a fixed PWM frequency of 20 Hz, varying the mark to space ratio, using the same PWM signal generator as above. The flow rate and PWM signals were plotted. The results showed that between 0 to 10 % PWM mark time (0 to 5 ms) the percentage max flow rate increases exponentially reaching a figure of 24 % of max flow rate at 10 % PWM mark time. From 10 to 90 % of PWM mark time (5 to 45 ms) the percentage max flow rate increases linearly from 24 to 100 % of max flow rate. Above 90 % of PWM mark time the percentage max flow rate is constant at 100 %. It is therefore possible to vary the flow rate linearly between maximum and minimum limits by varying the percentage PWM mark time between 0 to 90 %, keeping the PWM frequency constant at 20 Hz (see figure 7.19).



Pressure drop = 6 bar  
 PWM Frequency = 20 Hz

Figure 7.19 - Variation of the % max flow with % mark time.

### 7.8.3 Natural Frequency Analysis of the VJ114 Valve

A VJ114 valve was dismantled and analyzed, in order to provide information to calculate the valve's natural frequency  $f_n$ , since this could not be obtained from the manufacturer (SMC). The dimensions and mass of the valve poppet and stainless steel spring were measured and from spring theory the stiffness of the spring was calculated (see equation 7.17).

$$\text{Spring Stiffness } (K) = \frac{Gd^4}{8nD^3} = 0.198 \text{ N/mm} \text{ (} 198 \text{ N/m)} \quad (7.17)$$

Where: G = modulus of rigidity (Stainless Steel, 69 kN/mm<sup>2</sup>); d = diameter of wire (0.3mm); n = number of active coils (5.5); D = mean coil diameter (4mm).

The mass of the poppet was 0.7 grams and the natural frequency of the valve was therefore calculated to be 85 Hz  $\pm$  5% (see equations 7.18 and 7.19), this appears to be correct since the maximum flow condition occurs in this region and as a rule of thumb, operating up to about 1/5 of the natural frequency is accepted practice (ie up to ~ 20 Hz).

$$\text{Natural frequency of the mass-spring system } (\omega_N) = \sqrt{\frac{K}{m}} = 531.84 \text{ rad/sec} \quad (7.18)$$

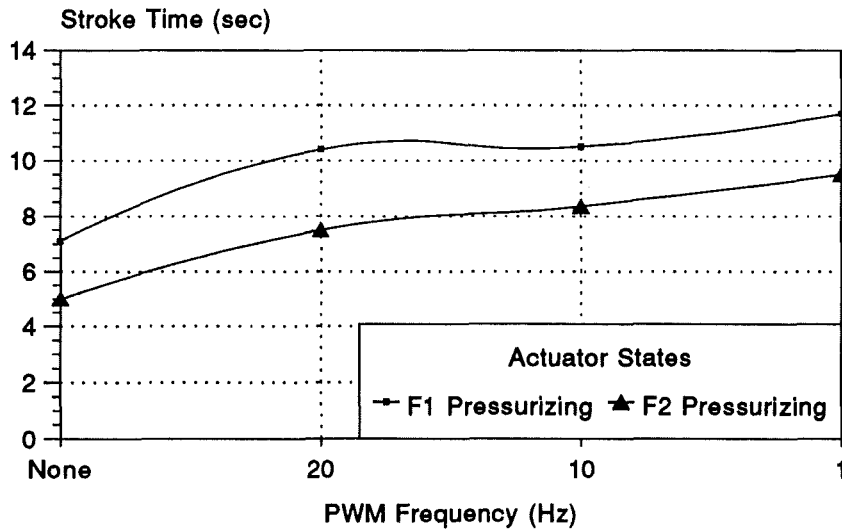
$$f_n = \frac{\omega_N}{2\pi} = 84.65 \text{ Hz} \pm 5\% \quad (7.19)$$

### 7.8.4 Testing of a Dual Flexator Actuator with PWM

Several different tests were conducted on the single-axis test-rig using 60 x 90 flexators. The system was operated using a PWM generator and a manual switch arrangement which allowed the flexators to be driven in either direction or in a neutral mode whereby all the valves were shut and the angular position maintained. This arrangement was used to drive the actuator between limits measuring the output variables of flexator pressure and angular position for various PWM frequencies of 1, 10 and 20 Hz and also with no PWM (see Appendix R). The figures in Appendix R illustrate the effect of the PWM frequency on stroke times and they also show that the flexator acts as a low pass filter, filtering out the pressure pulses thereby giving a fairly smooth angular output. The higher the PWM frequency, the smoother the angular displacement and the faster the stroke times (see figure 7.20).

Flow sensors were used on the test-rig to measure the flow into and out of the dual flexator actuator. By measuring the volume of the two expanded flexators it was





Actuator stroke = 237 deg  
 Load torque = 2.328 Nm  
 Flexator 1 opposing torque load

Figure 7.20 - Effect of PWM frequency on joint stroke times.

possible to estimate the variation in the volumes between venting and pressurizing (0.8%) and between each flexator (approx 7%), this shows the effect that manufacturing the flexator by hand can have on the symmetry and balance of a dual flexator actuator.

## 7.9 REDESIGN OF THE FIRST PROTOTYPE ARM

Having evaluated the first prototype system and determined the problems and their cause, it was now possible to enter the redesign phase of the project. This redesign phase would encompass the design and manufacture of a second prototype arm together with an improved proportional controller, based on the research conducted using PWM control of the VJ114 valves in Section 7.8.

### 7.9.1 Selection of the Second Prototype's Joint Actuators

As in Section 7.3, each axis of the prototype was analysed, in the light of the test results from Section 7.7, to determine whether the type of actuator selected for each axis was still the best choice.

#### 7.9.1.1 Joint 1 - vertical lift actuator

The large bending moment of the first prototype arm caused bending in the actuator's piston rod. An investigation of bending theory was undertaken to mitigate this situation.

From estimations of the maximum bending moment of the arm, this was found to be in the region of 53 Nm. From bending theory the maximum deflection  $y_{max}$ , of the piston rod tip in the horizontal direction and its maximum stress  $\sigma_{max}$ , can be calculated (see equations 7.20 and 7.21).

$$y_{max} = \frac{M_{max}}{EI} \cdot \frac{L^2}{2} \quad (7.20)$$

$$\sigma_{max} = \frac{M_{max}r}{I} \quad (7.21)$$

Where:  $M_{max}$  is the maximum bending moment;  $E$  is Youngs Modulus (210 GN/m<sup>2</sup>);  $I$  is the second moment of area of the cross-section;  $L$  is the stroke length (0.25 m);  $r$  is the radius of the piston rod. Table 7.10 shows the piston rod deflection and stress analysis for the different piston rod diameters available for this actuator.

**Table 7.10 - Piston Rod Deflection and Stress Analysis of Joint 1.**

| piston rod $\phi$ , d (mm) | $I = \frac{\pi d^4}{64}$ (m <sup>4</sup> ) | $y_{max}$ (mm) | $\sigma_{max}$ (MN/m <sup>2</sup> ) |
|----------------------------|--|----------------|-------------------------------------|
| 12                         | 1.018E-09                                  | 7.75           | 312.4                               |
| 14                         | 1.886E-09                                  | 4.18           | 196.7                               |
| 16                         | 3.217E-09                                  | 2.45           | 131.8                               |
| 18                         | 5.153E-09                                  | 1.53           | 92.6                                |

Alternative solutions to the problem were to replace the actuator with a stiffer device, add an additional guide to the original cylinder or increase the diameter of the piston rod to increase the stiffness and reduce the stress. Alternative actuators were too expensive and also heavy, as was the guide bearing attachment. It was therefore decided to change from a  $\phi 12$  to a  $\phi 16$  mm piston rod for the double-acting cylinder. The new cylinder selected was a DZH-40-250-PPV-A from Festo pneumatic Ltd. This cylinder has a slightly larger footprint of 62 x 40 mm and a length increase of 18.5 mm over the original cylinder. The overall mass of the cylinder was increased from 1.25 to 1.82 kg and the thrust and return forces are also higher, 754 and 633 N respectively. However, the cost of the new cylinder was the same as the original one.

#### 7.9.1.2 Joint 2 - shoulder joint actuator

The shoulder joint actuator was found from the testing phase to be adequate and therefore its design was used in the second prototype without modification.

### 7.9.1.3 Joint 3 - mode change joint actuator

As stated in Section 7.7 the original design incorporating the 60 x 90 dual flexator actuator inside link 1 did not function well, due to the size of the flexators being used and the need to miniaturize the actuator design. After considering alternative solutions, it was decided to use a double-acting single vane type pneumatic rotary actuator (CompAir Maxam Ltd, model Hi-Rotor type PRN030S: 180° stroke). The reasons for this choice were due to its small size  $\phi 64 \times 105$  mm, its low mass of 0.47 kg and its reasonable cost of £121 (see Appendix B1.2). Together with the actuator, a non-contact position sensor was purchased which would allow positional control of the joint.

### 7.9.1.4 Joint 4 - elbow joint actuator (see figure 7.3)

The original 60 x 170 dual flexator actuator for this joint had several problems. The joint itself was too long, and prevented the arm from moving close to a surface such as a table top. The flexators tended to pop out from under the webbing straps due to their adverse length to width ratio. The large stroke of the flexators caused frictional problems of the webbing straps on the surface of the actuator's outer tube. The mass of the actuator and its position meant that it contributed to the high bending moment of the arm about the first axis. The torque produced by this actuator was not enough to lift the maximum payload at maximum reach. It was decided to move the position of this joint inbound to the position of the original mode change joint, this joint could now also be moved inbound, thus reducing the bending moment.

To increase the torque output and prevent the flexators from sliding from under the webbing straps, a 102 x 130 type dual flexator actuator was chosen for this joint, this actuator was able to produce a torque of 11.25 Nm @ 3.5 bar gauge. The maximum torque requirement for this joint was calculated to be approximately 20 Nm. Therefore to transfer the drive through 90° and multiply the torque by a factor of two, it was decided to use a bevel gear stage of ratio 2:1 mounted at the original position of joint 4. This would multiply the torque output of this joint to at least 22.5 Nm. Unfortunately, due to the high torque values, plastic bevel gears could not be used and therefore steel gears had to be selected for this joint. Finally, the stroke of joint 4 was reduced to the minimum possible, ie 90°.

### 7.9.1.5 Joint 5 - wrist extension actuator

In view of the need to reduce the length and therefore the inertia of the arm, it was decided to reduce the length of the links and have a larger stroke for the prismatic joint at the wrist. A stroke for joint 5 of 160 mm was therefore chosen. The new

double-acting cylinder being a DSN-12-160-P from Festo pneumatic Ltd. This actuator had a size of  $\phi 20 \times 265$  mm, a mass of 146 grams and a cost of £28. When used at 6 bar it had a return force of 38 N, the same as the original cylinder. Instead of the two Aluminium alloy telescopic tubes it was decided to use a single tube running in a thermoplastic bush manufactured from 'Vesconite'.

#### 7.9.1.6 Joints 6, 7 and 8 - wrist yaw & roll and end effector grasp

Since these components were not manufactured for the first prototype they were not redesigned for the second prototype.

## 7.10 DESIGN OF THE SECOND PROTOTYPE ARM

The kinematic arrangement of the arm had not changed from that of the first prototype, however, some of the joint actuators and their strokes were different. This meant that the design variables had once more changed and therefore had to be recalculated. The next stage of the project involved the detailed design of the new components and the selection of the arm's structural details as shown in a computer simulation (Prior, 1993b). The control program written in Assembler had to be modified to cater for the improvements in the control algorithm but this did not affect the controller hardware components.

### 7.10.1 Detailed Mechanical Design (see Appendix S)

This part of the project consisted of designing the following components:

- *The connection between joint 2 and link 1;*
- *The mode change bearing arrangement;*
- *Link 1 structure;*
- *Potentiometer mounts;*
- *Joint 4 - the 102 x 130 dual flexator actuator;*
- *The bevel gear stage and bearing arrangement;*
- *The connection and housing between joint 4 and link 2;*
- *Link 2 structure;*
- *The mounting arrangement of the joint 5 actuator within link 2;*
- *The connection between joint 5 and the extension tube, and*
- *The extension tube, bearing and end cap.*

When selecting materials for the second prototype, it was decided that once again Aluminium alloy would be utilised together with stainless steel and carbon fibre tubing for some of the structural components, especially links 1 & 2.

#### 7.10.1.1 Selection of the link enclosure type

Based on the original research shown in Section 7.4.2, it was decided to once again use hollow circular cross-sectional profiles of straight length for links 1 & 2.

### 7.10.2 Factors Affecting the Optimum Design Variables

By redesigning the first prototype, the 60 x 90 dual flexator actuator was removed, thus allowing the diameter of link 1 to be reduced. However, the need to place the joint 4 actuator in joint 3's old position meant that the diameter of link 1 was matched to, and used for the outer tube of the joint 4 actuator. In this new design, the structure of link 1 was used as the outer tube for joint 4. By using very thin sections, the mass and therefore the inertia of the link was reduced. The dimensions for link 1 (joint 4 actuator) were set to  $\phi 1\frac{3}{4}$ " (44.45 mm) with a wall thickness of 0.064" (1.63 mm) for the outer tube, and  $\phi 1\frac{1}{8}$ " (28.58 mm) with a wall thickness of 0.048" (1.22 mm) for the inner drive shaft. Both of these tubes were seamless and manufactured from stainless steel (S.S.) grades 321 and 304 respectively. The advantages of using S.S. tubing were its high strength, low mass (thin section), corrosion resistance and by using hollow drive shafts, they could be used as ducts for carrying cabling. Link 2 was also reduced, to  $\phi 1\frac{1}{2}$ " (38 mm) with a wall thickness of 0.098" (2.5 mm). The material selected for link 2 was a structural fibreglass called 'Extren', which is a combination of fibreglass reinforcements and thermosetting polyester. The advantages of using 'Extren' were its corrosion resistance, low density (80% less than steel), high strength, dimensional stability and low cost (£2.43/m).

During the manufacture and assembly of the second prototype, difficulties occurred which changed the dimensions of some of the critical design parameters. The parameters involved were  $b_1$  which increased to 70 mm and  $b_3$  which decreased to 15 mm. The above changes to the optimum design meant that the parametric equations of Section 6.2 had to be recalculated to ensure that the arm could reach the desired workspace and to determine the arms reach characteristics.

From Equation 6.1:

$$Z = C + a_1 + b_1 + b_2 + b_3 + b_4 \quad (7.22)$$

$$Z = 220 + 414 + 70 + 44.45 + 15 + 38 \quad (7.23)$$

$$Z = 801.45 \text{ mm} \quad (7.24)$$

From Equation 6.2:

$$L2 = C + a1 + b1 + \left(\frac{b2}{2}\right) - x - G \quad (7.25)$$

$$L2 = 220 + 414 + 70 + \left(\frac{44.45}{2}\right) - 160 - 220 \quad (7.26)$$

$$L2 = 346 \text{ mm} \quad (7.27)$$

The home height ( $Z$ ) of the arm had therefore increased again to 801 mm, now 70 mm over the optimum design height and 64 mm above the average electric wheelchair's armrest height. This was caused by the large clearance  $b1$ , which was required to enable the flexators of joint 4 to clear the top of joint 1. The length of link 2 was calculated to be the same as in the first prototype, but the length of link 1, which housed joint 4, the bevel gear stage and the mode change bearing was reduced to 390 mm. This made the ratio of the link lengths 1.13:1 and the ratio of the arm length to the end effector length 3.34:1 Table 7.11 below shows the complete set of design variables and demonstrates how these affected the reach characteristics, bearing in mind that joint 4 now had a stroke of  $90^\circ$  only.

**Table 7.11 - Parametric Design Variables and the Second Prototype (Prior, 1993b).**

| a1  | a2  | b1 | b2    | b3 | b4 | C   | G   | L1  | L2  | x   | Z   | Vr   | Vr <sub>max</sub> | Hr <sub>max</sub> |
|-----|-----|----|-------|----|----|-----|-----|-----|-----|-----|-----|------|-------------------|-------------------|
| 414 | 250 | 70 | 44.45 | 15 | 38 | 220 | 220 | 390 | 346 | 160 | 801 | 1032 | 1702              | 521               |

### 7.10.3 Discussion of the New PWM Control Algorithm

From the tests conducted on the VJ114 solenoid valves, it was found that the flow rate could be modulated from minimum to maximum, in one of two ways:

- *By varying the PWM frequency between a range of about 1 to 100 Hz whilst maintaining a fixed mark to space ratio of 1:1.*
- *By varying the mark time of a fixed frequency PWM signal (20 Hz).*

The first technique is a special type of Pulse Frequency modulation (PFM), the second is a true PWM method and is commonly used for modulating hydraulic valves which have a finite frequency response. Unlike conventional proportional valve control whereby the signal to the valves is continuously varied, pulse modulation control uses a series of digital pulses which alternate the valve between on and off states. The ratio of on time to off time is known as the mark to space ratio and it is this ratio which controls the flow rate of the valve.

The technique of Pulse Width Modulation has some important advantages:

- *Dither effects caused by pulsing can produce excellent resolution;*
- *A simple low-cost on-off valve can be controlled as a proportional valve, and*
- *Valve gain can be regarded as constant.*

The pulse train polarity used in the control of the first prototype's valves was always positive and was set to 24Vdc. Once the user had selected the joint speed, (ie selected the PWM frequency, either 12.2 or 62.5 Hz) the controller would use this frequency to modulate the valves. However, although proportional in the sense that the valves were being digitally pulsed, the control system was still an on/off type with a preset deadband and was not related proportionally to the angular error signal of a joint.

Matching the choice of PWM frequency to the valve frequency response is extremely important, in the tests of the VJ114 valve it was found that the frequency of the PWM signal has an important effect on both the smoothness of the actuator drive and its stroke time. The higher the frequency, the smoother the output and the faster the stroke time. However, from manufacturer's data and analysis of the VJ114 valve it was decided to set the PWM frequency for driving the valves to 20 Hz. In the new control algorithm it is proposed that by dynamically changing the mark to space ratio, in response to a servo loop positional error signal, the effective opening of the VJ114 valves, and hence their flow rate can be dynamically modulated.

For example, if a dual flexator actuator had a stroke of 0 to 180° with a memory location set at the 90° position and was displaced by an external force to the 0° position, the joint potentiometer would register an error signal of 90°. In the proposed control algorithm, the flow rate of the control valve would be proportional to the error and thus at 0° position the flow rate would be a maximum, ie the PWM signal with a 90% mark time (45 ms) and a 10% space time (5 ms), as the joint approached the target these values would change to become a 10% mark time and 90% space time, thus limiting joint overshoot and oscillation. The use of a deadband space ( $\pm 3^\circ$ ), in which all the valves are closed has also helped to reduce oscillations about a set position.

## 7.11 CONCLUSIONS

This has been a wide ranging study, covering many different areas of work, from design and analysis, to manufacture and testing. The design and development of each stage of the prototype arm has been presented in detail and significant conclusions have been reached.

This project has been driven primarily by the constraints of cost, mass and safety, amongst many others, this tended to bias design decisions towards pneumatic systems, with the result that the second prototype design was compliant and therefore of low precision. However, due to the type of tasks envisaged for this device and the implicit safety features of pneumatics, this has not caused many problems. Further precision can be achieved by the fine position control of the wrist section of the manipulator.

The fundamental research into the flow analysis of the VJ114 miniature solenoid valves has shown that the flow regimes in the valves and manifold can become turbulent. The simple laminar flow equation (used by the manufacturer of the valve), was based on low pressure drops and was derived from liquid flow analysis. This equation when used with large pressure drops was shown to be inaccurate and therefore could not be used.

The mathematical modelling of the mass flow rates based on the techniques originally developed by Sanville have been used with success to accurately model the flow of the complex dual flexator pneumatic rotary actuator. Matching these results with empirical data, it has been possible to estimate the value of the critical pressure ratios operating in this pneumatic system (0.15). The value of the critical pressure ratios have been noted to be much lower than the standard value of 0.528, and compare closely with the results of earlier researchers.

Tests using pulse width modulation (PWM) of the control valves has shown their limited frequency response and corresponding flow rates. By varying the mark to space ratio of the valves it has been shown that it is possible to linearise the flow rate, and hence a proportional control algorithm has been implemented in the ACSL simulation.

The design of the second prototype incorporates all the original design features of the first system, as well as reducing the arms inertia, making the joints more functional and improving the aesthetics. Further work is required to fully test the new design and report on further improvements.



# Chapter 8

## CONCLUSIONS & FURTHER WORK

---

*'This is not the end. It is not even the beginning of the end.  
But it is, perhaps, the end of the beginning.'*  
Winston Churchill, 1942.

---

### 8.1 CONCLUSIONS

The aim of this research was to investigate novel design and construction aspects of a rehabilitation manipulator which can perform the tasks that disabled people would most like to be able to do, at a cost the majority could afford. To appreciate many of the aspects covered in this thesis the reader should view the accompanying video tape. This illustrates the result of a number of stages in the research programme.

The first step towards this goal involved research into the areas of human factors, ergonomics, anthropometrics and statistics related to disability, especially those factors concerning wheelchair-bound individuals. Although information in these areas was scarce, data was collected from a number of sources and was used in the initial conceptual phase of the project.

The numbers of disabled people in any industrialised nation was found to be approximately 12% of the adult population, with approximately 1 in 120 of these being electric wheelchair users. Due to the worldwide aging population, these figures will increase significantly during the next decade.

Human factors research regarding the performance of the human arm established criteria for an anthropomorphic type rehabilitation manipulator. The link lengths should be in a ratio of 1.1:1, and the ratio of the length of the arm to the hand should be approximately 2.8:1. The arm should also show a reduction in cross-section, when approaching the hand from the shoulder joint.

Previous research showed that an anthropomorphic design of manipulator benefits from its similarity to the human arm configuration as it is more easily controlled by the user's subconscious control system, which has evolved over several thousands of years (Corker et al, 1979).

The design of a wheelchair-mounted manipulator should therefore follow the design of the human arm, but should not try to imitate it in terms of appearance. It must be reliable, safe, easy to operate and be of reasonable cost.

**Table 8.1 - Component Costs of the Second Prototype.**

| <b>Component Description</b>                  | <b>Cost (£)</b>  |
|---|------------------|
| Miniature electrical solenoid valves (20 off) | 534.39           |
| Vane type actuator & sensor                   | 204.69           |
| Air compressor                                | 189.00           |
| Controller components (including keypad)      | 140.00           |
| Joint 1 double-acting cylinder                | 125.00           |
| Ancilliary components                         | 50.00            |
| Stainless steel tubing (link 1)               | 43.17            |
| Joint 5 double-acting cylinder                | 38.77            |
| Bevel gears                                   | 35.84            |
| Reservoir                                     | 30.00            |
| Tube connectors                               | 30.00            |
| Joint 2 double-acting flexator                | 30.00            |
| Joint 4 double-acting flexator                | 30.00            |
| Aluminium alloy tubing (link 2 extension)     | 20.00            |
| Manifold                                      | 15.00            |
| Compressed air tubing                         | 10.00            |
| Carbon fibre tubing (Link 2)                  | 1.21             |
| <b>Total</b>                                  | <b>£1527.07p</b> |

The costings in Table 8.1 are based on one-off purchases at commercial prices and are inclusive of VAT @ 17.5% as well as delivery, handling and other charges. The manufacturing cost of the arm would probably raise the cost to around £3,000. After adding a profit margin of 30% this would lead to a retail price of approximately £4,000.

The need for a wheelchair-mounted manipulator amongst the disabled community was established. If the final cost of the system was £4,000 a substantial market exists for this type of product.

A review of rehabilitation robotics research highlighted the diversity of work within this small area. The choice between a mobile or a workstation based system dictated, to a large extent, the type of robot used, the cost of the project and its duration. Workstation systems tended to use educational/industrial robots, whereas mobile systems tended to develop purpose-built manipulators. There is undoubtedly a need for both systems, and it is interesting to note that several surveys have shown that users of workstation systems requested wheelchair-mounted versions of these systems to be developed. Several research groups throughout the world are now developing wheelchair-mounted versions

of their workstation based systems. However, from an initial analysis, their working envelope will not cover the full design specification achieved in this programme, without major alterations to their kinematic designs.

The review of wheelchair-mounted manipulator projects highlighted several different approaches (see Table 8.2). However, all the earlier systems failed to reach production, due to one or more critical deficiencies. A summary of the essential requirements of a rehabilitation manipulator was established. Namely the system should:

- *have a low mass (<10 kg);*
- *have a maximum payload of between 1 - 2 kg;*
- *have a reach of between 0.7 - 0.9 m;*
- *have several modular interfaces;*
- *have several control modes, ie joint, velocity, end point;*
- *have reprogrammable memory;*
- *be dextrous;*
- *be reliable;*
- *be easy to learn and use;*
- *be of reasonable cost.*
- *be safe;*

From Table 8.2, the Middlesex manipulator shows great potential, meeting the most essential requirement of reprogrammability. The only other system with this feature, the Manus arm, excels but at a high cost, which will probably prevent its widespread use.

A common problem amongst previous projects was the lack of input from the intended users of the device as to what their needs and abilities really were. The Middlesex questionnaire survey, for the first time, identified the characteristics of electric wheelchair users and evaluated their needs and abilities. A task list was established which contained the top 18 tasks most required by a disabled person and has collated those easiest to perform in terms of a rehabilitation manipulator.

The specification was the central point in the design process and provided a bridge between the data on one side and the kinematic design on the other. Of all the design requirements, the most influential in terms of the kinematic design was the need to reach down to the floor level as well as up to a high shelf height. Without this requirement the design would have been much simpler, requiring at least one degree of freedom less. However, this requirement was deemed essential by the survey subjects, and therefore had to be met.

Table 8.2 - Summary of Wheelchair-Mounted Manipulator Designs (Extended from Leifer, 1981).

| Project Title                           | D.O.F & Joint Types | Start Date | Mass (kg) | Payload (kg) | Reach (m) // Workspace | End Effector Type | User Interface                         | Control Modes                  | Reprogrammable Memory | Drive Type    | Manipulation Capability | Reliability | Feedback    | Learning Difficulty | Cost (\$)     |
|---|---------------------|------------|-----------|--------------|------------------------|-------------------|--|--------------------------------|-----------------------|---------------|-------------------------|-------------|-------------|---------------------|---------------|
| Rancho Los Amigos Hospital <sup>‡</sup> | 6<br>(6R, 0P)       | '67        | N/A       | 1            | N/A                    | 2 finger hook     | 6 tongue switches<br>2 dof joystick    | joint on/off velocity          | no                    | elect.        | v. low                  | high        | no          | v. high             | low           |
| V.A. Rehabilitation Center              | 4<br>(3R, 1P)       | '73        | 20        | 2            | Ø2.5                   | "                 | 5 pos. switch<br>2 dof joystick        | cartesian velocity             | no                    | elect.        | low                     | med.        | proj. image | low~ med.           | med.          |
| Jet Propulsion Lab.                     | 6<br>(5R, 1P)       | '75        | 20+       | 1            | "                      | "                 | 36 words<br>(voice control)            | joint on/off, vel.             | no                    | elect.        | low                     | low         | no          | high                | high          |
| Spar Aerospace // O.C.C.C.              | 5<br>(3R, 2P)       | '77        | 23        | 2.3          | 0.86                   | prosthetic hand   | 2 pos. switch<br>3 dof joystick        | joint velocity                 | no                    | elect.        | v. low                  | med.        | led         | high                | high          |
| University of Virginia                  | 5<br>(3R, 2P)       | '78        | 23+       | 2.3          | 0.86                   | "                 | 5 levels<br>2 dof joystick             | "                              | no                    | elect.        | low                     | med.        | vdu         | med.~ high          | high          |
| Zeelenberg // N.J.M.S.                  | 5<br>(5R, 0P)       | '82        | 9         | 0.5          | 0.48                   | 2 jaw prismatic   | 15 key keypad<br>joystick              | joint on/off                   | no                    | elect.        | med.                    | med.        | no          | low                 | \$4000 (1986) |
| IR V Holland (Manus Manipulator)        | 7<br>(6R, 1P)       | '84        | 20        | 1.5          | 0.8                    | 2 jaw prismatic   | multiple                               | joint cartesian velocity       | yes                   | elect.        | high                    | high        | yes         | low                 | 25,000 (1991) |
| Inventaid Manipulator                   | 6<br>(6R, 0P)       | '86        | N/A       | 2            | 0.9                    | "                 | keypad,<br>joystick,<br>tongue control | joint on/off                   | no                    | pneu.         | med.                    | med.~ high  | no          | low                 | 5,000 (1992)  |
| Middlesex Manipulator                   | 7<br>(5R, 2P)       | '88        | 8         | 1            | 0.64 <sup>†</sup>      | N/A               | 16 key keypad<br>(modular)             | joint on/off velocity position | yes                   | elect.~ pneu. | med.                    | N/A         | yes         | N/A                 | 4,000 (est.)  |

‡ - The Rancho Los Amigos arm was originally an orthotic device which supported the users arm, whereas all the other devices are classified as rehabilitation manipulators.

† - The reach characteristic does not include the length of the wrist/end effector.

R = Revolute joint, P = Prismatic joint.

All the above systems were purpose-built, with the exception of the educational robots used by Zeelenberg / New Jersey Medical School.

The 'scariculated' kinematic design used in the wheelchair application combined two different forms of industrial robot configuration. It was therefore novel and appeared to have great potential. This arrangement permits both floor and high shelf reach, as well as having a normal SCARA mode which was non-compliant in the vertical plane and compliant in the horizontal plane.

The flexator actuator was a vital component in the design of the Middlesex manipulator. It provided a reliable, safe, smooth and low cost form of actuation, together with a high  $T_p/MM$  ratio of approximately 19 Nm/kg (see Table 8.3). The need for safe operation, and yet accurate positioning, has led to the use of hybrid drive systems combining pneumatic and electrical actuation.

**Table 8.3 - Comparison Between Conventional Pneumatic and Hydraulic Direct-Drive Rotary Actuators and the Dual Flexator.**

| Manufacturer & Model          | Actuator Type & Stroke | Dimensions (mm) |       |        | Motor Mass (kg) | Peak Torque (Nm @ 6 bar)   | $T_p/MM$ (Nm/kg)        | Cost (£) (ex VAT) |
|-------------------------------|------------------------|-----------------|-------|--------|-----------------|----------------------------|-------------------------|-------------------|
|                               |                        | Height          | Width | Length |                 |                            |                         |                   |
| Airmuscle 42 x 90             | Dual Flexator 280'     | ∅ 63.5          | /     | 130    | 0.7             | 11.83                      | 16.9                    | 30                |
| Airmuscle 102 x 130           | Dual Flexator 280'     | ∅ 63.5          | /     | 254    | 1.3             | 24.24                      | 18.7                    | 40                |
| CompAir Maxam PRN050S         | Single Vane 280'       | ∅ 79            | /     | 145    | 0.7             | 5.9                        | 8.4                     | 132.90            |
| Festo DSRL ∅32                | Single Vane 184'       | 92              | 130   | 126    | 1.285           | 10                         | 7.8                     | 158.83            |
| Tol-o-matic 1817-0201         | Single Vane 280'       | 63.5            | 63.5  | 133.4  | 0.909           | 8.14                       | 9.0                     | 171.02            |
| SMC CRA1-BS100                | Rack & Pinion 184'     | 172             | 112   | 311    | 0.968           | 9                          | 9.3                     | 458.13            |
| Kinetrol 02-100               | Single Vane 90'        | 76              | 93    | 70     | 0.44            | 10.16                      | 23.1                    | 41.97             |
| (Hydraulic) Hydroac HS-1.5-1V | Single Vane 280'       | ∅ 158.75        | /     | 155.5  | 13.182          | 13.67<br>(455.6 @ 210 bar) | 1.0<br>(34.6 @ 210 bar) | 1047              |

A review of direct-drive pneumatic, hydraulic and electrical rotary actuators showed that the flexator actuator was comparable with all but the largest conventional actuators and one of the lowest in terms of cost. By using dual flexators, double-acting control of a revolute joint was achieved together with control over its compliance. The flexator was found to be best suited to applications where miniaturisation of the actuator was not a requirement.

The torque produced by this type of actuator was modelled and shown to be a function of six independent variables:

$$T = f(P, R, r, R_h, \gamma, \alpha) \quad (8.1)$$

These variables relate the driving torque,  $T$  to the flexator chamber pressure,  $P$ , the actuator parameters,  $R$  and  $r$ , and the flexator parameters,  $R_h$ ,  $\gamma$  and  $\alpha$ .

The flexator actuator, like many other pneumatic devices, has a high degree of hysteresis associated with its performance. The level of hysteresis was found to reduce significantly by using the following methodology:

- *Provide low friction bearings in the actuator;*
- *Manufacture the flexator and webbing strap from non-elastic materials of high Young's Modulus;*
- *Avoid using the flexator actuators where  $\gamma > 180^\circ$ ;*
- *Use values above 40 mm, for the outer tube diameter, R;*
- *Use wider flexators rather than longer ones;*
- *Use the flexator actuator at higher supply pressures;*
- *Reduce the frictional effects of the webbing straps, by the use of rollers or friction reducing PTFE strips, and*
- *Reduce the movement of the flexators by careful design of the actuator.*

The flexator actuator together with its pneumatic control valves and subsystem was analyzed and accurately modelled using one-dimensional compressible flow theory. The derived mass flow rate equations, when using suppressed critical pressure ratios,  $b_1$  and  $b_2$  of 0.15, was shown to be accurate to within +2.5% for charging and +5% for venting.

The results of this analysis was used successfully in an ACSL program to simulate a typical dual flexator actuator. This program can be easily modified to simulate a system consisting of any size of flexator, system inertia and valve type. Pulse width modulation (PWM) of the miniature solenoid valves used in the prototype enabled the flow rate of the valves to be varied in proportion to the mark/space ratio of the PWM signal.

The type of control used in the simulation was a proportional error based algorithm, this being one of the easiest to implement on the prototype. However, more advanced control methods such as PD, PI or PID could be explored, through simple modifications to the control algorithm.

The realisation stage of the project enabled the kinematic design of manipulator to be integrated with the most appropriate form of actuation for each of the manipulator's joints, the final design being that of an electro-pneumatic hybrid device. The second prototype incorporates all the original design concepts of the first prototype, as well as reducing the arm's inertia, making the joints more functional and improving the aesthetics of the arm.

Throughout the civilised world, on every road there can be seen vehicle-mounted hydraulic manipulators, operated by semi-skilled HGV drivers. These systems were

introduced quietly and without much fuss over the last decade. They were regarded as manipulators and so did not suffer from the stringent safety standards that relate to the word 'robot'. The same cost criteria used for these devices could also be applied to rehabilitation manipulators so that introduction of these systems can become just as widespread and commonplace.

Current safety regulations prohibit the entry of a human into the workspace of an industrial robot during normal operation. These regulations cannot therefore be applied to the area of rehabilitation robotics. It is essential that designers of assistive robotic devices, define a workable standard by which all such systems should conform. This standard would therefore act as the state of best practice. Whereas safety is a legal requirement it must be noted that no system is 100% safe and that sooner or later accidents will occur. The designers task is therefore to create a system which is as safe as possible and which can be produced at a cost the majority can afford.

People with disabilities have often been regarded as second class citizens and a burden on the state. This view is both outdated and unwarranted. Wheelchair-mounted manipulators have the ability to significantly improve the lives of disabled and elderly people.

A central theme in rehabilitation robotics is vocational rehabilitation, and this is currently one of the research thrusts of the EC TIDE initiative (1991-96). Once people with disabilities are able to work, and therefore earn an income, they can contribute to the state. Their self esteem can increase and their value to society could at last be truly realised.

## **8.2 FURTHER WORK**

### **8.2.1 Introduction**

The dual flexator, although a highly original and effective actuator, can still be improved further. The concept behind the prototype rehabilitation manipulator developed at Middlesex has been proved. The design of the manipulator can be optimised and further work can be undertaken in the following areas.

### **8.2.2 Improvements to the Dual Flexator Actuator**

The design of the dual flexator actuator used throughout this project was based on the original system developed by Jim Hennequin. Further work is therefore required to

reduce the mass of the actuator by using low density, high modulus materials such as carbon fibres and plastics. The design of the actuator needs to be investigated to find ways of reducing the hysteresis characteristic. This would involve the use of new non-elastic materials of high Young's Moduli for the flexators and webbing straps and friction-inhibiting designs.

### **8.2.3 Development of the ACSL Simulation Model**

A more refined simulation model could be produced by using more sophisticated functions to represent many of the flexator characteristics, ie friction. Further tests are needed to determine the validity of the bi-directional ACSL model with proportional error feedback. At this stage more advanced control algorithms could be implemented and comparisons with the simple proportional error model could be made.

### **8.2.4 Design of the Wrist and End Effector for the Middlesex Manipulator**

The design of the wrist and end effector was not researched in depth during this project. However, the broad requirements of a two degree of freedom wrist and a parallel jaw end effector which could open to a maximum of 80 mm was established. Further work is required to produce detailed designs for the wrist and to determine whether to use a single dextrous end effector or a series of interchangeable end effectors, each capable of specific tasks.

### **8.2.5 Investigations into the Role of Preprogrammed and Direct Teleoperation with Reference to the Priority Task List**

Once the second prototype is fully functional, investigations are required into the role of preprogrammed and teleoperation, with reference to the priority task list developed in chapter 3. This work will help to further improve the user interface design by testing the use of joysticks, tongue controllers, etc.

After safety and reliability trials have been conducted in the laboratory, the next step is to mount the system onto an electric wheelchair and test the full system in the home environment using volunteers, some of whom may have taken part in the original questionnaire survey. The feedback and follow-up gained from this stage will be used in a redesign phase. At this point, new developments in linear pneumatic actuators, such as built-in position sensing and locking features, may be incorporated into a new/redesigned prototype.



## *List of References*

---

1. Andeen, G.B. (ed) (1988) Robot Design Handbook, (London, SRI International).
2. Asada, H., Kanade, T. and Reddy, R. (1981) 'Design concept of direct-drive manipulators using rare-earth dc torque motors', Proceedings of the 11th International Symposium on Industrial Robots, 7-9 October, pp.629-636, (Sobim & JIRA).
3. Bach, J.R., Zeelenberg, A.P. and Winter, C. (1990) 'Wheelchair-mounted robot manipulators : Long term use by patients with duchene muscular dystrophy', American Journal of Physical Medicine & Rehabilitation, Vol. 69, No. 2, pp.55-59.
4. Baldwin, H.A. (1969) Realizable models of muscle function, Biomechanics Proceedings of the 1st Rock Island Biomechanical Symposium, (Plenum Press), pp.139-148.
5. Biscoe, G.I. and Mills, A.S., (1988) 'Actuator for robotic applications', Measurement and Control, 21, April, pp.76-79.
6. Cakebread, R., (1982) 'Hydraulic vs electric drives for robots', Hydraulic Pneumatic Mechanical Power, 28, 1, pp.24-25.
7. Cameron, W.M., (1988) 'Rehabilitation Research & Development Network Bulletin', Neil Squire Foundation, Vol. 1, No. 4, November.
8. Cammoun, R., Detriche, J-M. and Lesigne, B. (1992) 'Optimization of the robotized system master after its clinical evaluation', Proceedings of the 1992 International Conference on Rehabilitation Robotics, Sept. 15-16, Keele University.
9. Clay, T.P., Hillman, M.R., Orpwood, R.D. and Clarke, A.K., (1987) 'A survey of the potential users of a robotic aid system', Royal National Hospital for Rheumatic Diseases and The Bath Institute of Medical Engineering.
10. Clemente, C.D., (1987) 'Anatomy - A regional atlas of the human body', 3rd Edition, (Munich, Urban & Schwarzenberg).

11. Coiffet, P., (ed) (1987) Modelling and Control, Robot technology, Volume 1, (London, Kogan Page), p.25.
12. Collie, A., (1992) 'Unusual robots', Industrial Robot, 19, 4, pp.13-16.
13. Colton, B., (1988) 'The robot arm that listens and obeys', The Times, July 21<sup>st</sup>, p.11.
14. Considine, D.M., (1986) 'Robot technology fundamentals', In: Standard Handbook of Industrial Automation, (London, Chapman & Hall), pp.281-283.
15. Corker, K., Brenner, M. and Lyman, J., (1978) 'The development of criteria for evaluation and prescription of remote medical manipulators', Proceedings of the Conference on Advances in External Control of Human Extremities, Dubrovnic, Yugoslavia, (ETAN).
16. Corker, K., Lyman, J. and Sheredos, S., (1979) 'A preliminary evaluation of remote medical manipulators', Bulletin of Prosthetics Research, 10-32, Fall, pp.107-134.
17. Croney, J., (1971) Anthropometrics for Designers (London, B.T. Batsford Ltd).
18. Czarniecki, C.A., Ashworth, M.J. and Towill, D.R., (1988) 'Dynamic modelling of a three-axis pneumatic robot', Transaction of the Institute of Modelling and Control, 10, 1, pp.50-56.
19. Dallaway, J.L. and Jackson, R.D., (1992) 'RAID - A vocational robotic workstation', Proceedings of the 1992 International Conference on Rehabilitation Robotics, Sept. 15-16, Keele University.
20. Davies, B.L., (1984) 'The use of robots to aid the severely disabled', Electronics & Power, pp.211-214.
21. Davies, B.L., (1987) 'Robotics, manipulation & environmental control', IEE Colloquium on Systems for the Disabled, IEE Vol. 25, pp.5/1-5/3.
22. Davies, B.L., (1993) 'Safety of medical robots', Proceedings of the 7th International Conference on Advanced Robotics '93 ICAR, Tokyo, Japan, November, pp.311-317.

23. D.H.H.S., (1982) '1978 Survey of Disability and Work', U.S. Department of Health and Human Services, U.S.G.P.O., Washington, D.C.
24. Diffrient, N., Tilley, A.R. and Bardagjy, (1974) Humanscale 1/2/3 Manual, (Massachusetts, The MIT Press).
25. Drazan, P.J., and Thomas, P.B., (1978) 'Simulation of an electro-pneumatic manipulator system', Proceedings of the Fifth International Fluid Power Symposium, Durham, 13-15 September 1978, Paper C5, pp.59-72.
26. Drazan, P.J., (1983) 'Control of robot dynamics by microcomputer', In: Robotic Technology, edited by A. Pugh, (London, P. Peregrinus Ltd, 1983), pp.38-51.
27. Dymond, E.A., Potter, R., Griffiths, P.A. and McClemon, E.J., (1988) 'A week in the life of mary: The impact of microtechnology on a severely handicapped person', The Journal of Biomedical Engineering, 10, 6, pp.483-490.
28. Edholm, O.G., (1967) 'The biology of work', In: Muscular work, (London, Wiedenfeld and Nicolson).
29. Editor, (1981) New Internationalist, No.95, January.
30. Editor, (1984) Biomedical Business International, No.7, pp.192.
31. Editor, (1988) 'Progress Reports', Rehabilitation, Research and Development Center, Veterans Administration Medical Center, Palo Alto, CA.
32. Editor, (1991) Robot Facts 1991 - Annual Report of UK Investment in Robot Automation in Manufacturing Industry, British Robot Association.
33. Engelberger, J.F., (1990) 'ICORR 90 Keynote speech', Proceedings of the International Conference on Rehabilitation Robotics, Wilmington, Delaware, June 14-15, pp.1-11.
34. Engen, T., (1964-67) 'Powered upper extremity orthotic development', Progress Reports, Texas Institute for Rehabilitation and Research.
35. E.P.W., (1984) 'Rubber muscles take robotics one step further', Rubber Developments, Vol. 37, No. 4, pp.117-119.

36. Faletti, M.V. and Clark, M.C., (1984) 'Task analysis in the person-robot-environment triad', Tower Conference Management Interobot West, 2nd International Conference Long Beach, CA, pp.126-143.
37. Fengler, M., (1988) 'Robots in rehab - part II', Neil Squire Foundation Newsletter, Vol. 2, No. 4, Summer, pp.5-8.
38. Finlay, P.A., (1988) Applications for Advanced Robotics in Medicine and Healthcare, Feasibility study report, No. R1175/1, January.
39. Floyd, W.F. et al, (1966) 'A study of the space requirements of wheelchair users', Paraplegia, Vol. 4, No. 1, pp.24-37, May.
40. French, I.G. and Cox, C.S., (1990) 'Modelling, design and control of a modern electropneumatic actuator', IEE Proceedings, Vol. 137, Pt. D, No. 3, pp.145-155.
41. Fu, C., (1986) 'An independent vocational workstation for a quadriplegic', Proceedings of the 9th Annual RESNA Conference, Minneapolis, Minnesota, pp.182-184.
42. Gavrilovic, M.M. and Maric, M.R. (1969) 'Positional servo-mechanism activated by artificial muscles', Medical & Biological Engineering, Vol. 7, pp.77-82.
43. Glass, K. and Hall, K., (1987) 'Occupational therapists' views about the use of robotic aids for people with disabilities', The American Journal of Occupational Therapy, 41, 11, pp.745-747.
44. Goldsmith, S., (1977) Designing for the Disabled, (London, R.I.B.A.).
45. Gosine, R.G., Harwin, W.S. and Jackson, R.D., (1988) 'CURL: A programming environment for a rehabilitation robot', Proceedings of the First International Workshop on Medical and Healthcare Robotics, Ottawa, Canada, pp.6.1-6.10.
46. Grodski, J.J. and Immega, G.B., (1988) 'Myoelectric control of compliance on a ROMAC protoarm', Proceedings of the International Symposium on Teleoperation and Control, July, pp.297-308.

47. Gunderson, J.R., (1985) 'Interfacing the motor-impaired for control and communication', In: Electronic Devices for Rehabilitation, edited by J.G. Webster, A.M. Cook, W.J. Tompkins and G.C. Vanderheiden (London, Chapman & Hall Medical), pp.190-229.
48. Haggard, H.W., (1946) 'Mechanics of human muscle', Mechanical Engineering, Vol. 68, pp.321-324.
49. Harwin, W.S. and Jackson, R.D., (1985) 'Towards voice control of robotic aids for the disabled', Proceedings of the 8th Annual RESNA Conference on Rehabilitation Technology. pp.274-276.
50. Harwin, W. S., Ginige, A. and Jackson, R.D., (1986a) 'A potential application in early education and a possible role for a vision system in a workstation based robotic aid for physically disabled persons', In: Monograph 37: Interactive Robotic Aids - One Option for Independent Living, edited by R. Foulds, (New York, World Rehabilitation Fund), pp.18-23.
51. Harwin, W. S., (1986b) 'Critical appraisal of world research on robotic aids for the physically disabled', Cambridge University Engineering Department Report, 9pp.
52. Harwin, W.S. et al, (1988) 'A robot workstation for use in the education of physically handicapped', IEEE Transactions on Biomedical Engineering. 35, 2, pp.127-131.
53. Hennequin, J., (1991) 'Inventaid current research and progress', Proceedings of the 2nd Cambridge Workshop on Rehabilitation Robotics. CUED/B-ELECT/TR82. pp.29.
54. Hillman, M.R., (1987a) 'A feasibility study of a robot manipulator for the disabled', The Journal of Medical Engineering & Technology, 11, 4, pp.160-165.
55. Hillman, M.R., (1987b) 'Robotics for the handicapped in the US', Bath Institute of Medical Engineering Report, 30pp.
56. Hogan, N., (1984) 'Adaptive control of mechanical impedance by coactivation of antagonistic muscles', IEEE Transactions on Automatic Control, Vol. AC-29, No. 8, pp.681-690.

57. Hope, K., (1992) 'Zero backlash actuator will hold without drift', OEM Design, pp.6.
58. Huntingford, J., (1988) 'Characteristics of steppers, dc servos and brushless motors', Unimatic News, No. 4, Autumn/Winter, pp.8-9.
59. Immega, G.B., (1986) 'ROMAC muscle powered robots'. Proceedings of the Robotics Research Conference, SME Technical Paper No. MS86-777, pp.1-7.
60. Jackson, R.D., (1987) 'Report on a visit to French work on rehabilitation robotics', April 6-8, Cambridge University Engineering Department Report, 6pp.
61. Jacobsen, S.C., Iversen, E.K., Knutti, D.F., Johnson, R.T. and Biggers, K.B., (1986) 'Design of the Utah/M.I.T. dextrous hand', Proceedings of the IEEE International Conference on Robotics and Automation, San Francisco, 3, pp.1520-1532.
62. Jones, T., (1988) 'Out of the lab and into the home', Proceedings of the Joint Coordinating Forum for the International Advanced Robotics Programme, National Research Council of Canada, Ottawa, Ontario, pp.8.1-8.2.
63. Korba, L.W., (ed) (1989) 'International inventory of robotics projects in the healthcare field', National Research Council of Canada Report, NRCC No. 30379.
64. Kapandji, I.A., (1980) The Physiology of the Joints : Annotated Diagrams of the Mechanics of the Human Joints, Vol. 1, Upper Limb, (London, E&S Livingstone).
65. Kiessling, E.A., (1961) 'Carbon dioxide as a source of external power for prosthetic devices', The Application of External Power in Prosthetics and Orthotics, Appendix E, Publ. 874, (Washington, D.C., National Academy of Sciences), pp.79-87.
66. Kwee, H.H., (1986) 'Spartacus and manus: Telethesis developments in France and in the Netherlands', In: Monograph 37 : Interactive Robotic Aids - One Option For Independent Living, (New York, World Rehabilitation Fund), pp.7-17.
67. Kwee, H.H., Duimel, J.J., van Woerden, J. and Smits, J., (1987) 'Development of the manus wheelchair-bourne manipulator: a progress report', Proceedings of the 10th Annual RESNA Conference, San Jose, CA, pp.781-783.

68. Kwee, H.H. and Duimel, J.J., (1988a) 'The manus wheelchair-bourne manipulator', 1st International Workshop on Robotic Applications in Medical & Healthcare, Ottawa, Canada, pp.4.1-4.5.
69. Kwee, H.H. and Duimel, J.J., (1988b) 'The manus wheelchair-mounted manipulator: Developments towards a production model', Proceedings of the International Conference of the Association for the Advancement of Rehabilitation Technology, Montreal, Canada, June, pp.460-461.
70. Kwee, H.H., Duimel, J.J., Van Woerden, J.A., Driessen, L.W., Kolk, L.W., Rosier, J.C., de moed, A.A and van der Burght, R.J.M., (1991) 'The manus telethesis : A progress report', Proceedings of the Second Cambridge Workshop on Rehabilitation Robotics, Selwyn College, April 12-14, CUED/B-ELECT/TR82.
71. Leifer, L. et al, (1978) 'Robotic aids for the severely disabled: feasibility assessment', Advances In External Control of Human Extremities, August 28-September 1, Dubrovnic, Yugoslavia, (ETAN).
72. Leifer, L., (1981) 'Rehabilitative robotics', Robotics Age, 3, 3, pp.4-15.
73. Liegeois, A. and Dombre, E., (1979) 'Analysis of industrial robots: relationships between structure, performance and function', Report of IRIA, No.79102 (Project SURF).
74. Liu, Y., Huston, R.L and King, T.P., (1984) 'Analysis of human body dynamics in the frequency domain', In: Trends in Ergonomics/Human Factors I, edited by A. Mital, (Amsterdam, Elsevier Science Publishers B.V.).
75. Makino, H. and Furuya, N., (1980) 'Selective compliance assembly robot arm', Proceedings of the 1st International Conference on Assembly Automation, March, (IFS Publications Ltd), pp.77-86.
76. Makino, H., Furuya, N., Soma, K. and Chin, E., (1980) 'Research and development of the SCARA robot', Proceedings of the 4th International Conference on Production Engineering, August, (Japan Society of Precision Engineering), pp.885-890.
77. Makino, H. and Furuya, N., (1981) 'Motion control of a jointed arm robot utilizing a microcomputer', Proceedings of the 11th International Symposium on Industrial Robots, October, (Japan Industrial Robot Association), pp.405-412.

78. Makino, H. and Furuya, N., (1982) 'SCARA robot and its family', Proceedings of the 3rd International Conference on Assembly Automation, (IFS Publications Ltd), pp.433-444.
79. Mannetje, J.J., (1981) 'Pneumatic servo design method improves system bandwidth twenty-fold', Control Engineering, June, pp.79-83.
80. Martin, J., Meltzer, H. and Elliot, D., (1988) 'The prevalence of disability among adults', Office of Population Censuses and Surveys, Social Survey Division, H.M.S.O.
81. Martin, J., White, A. and Meltzer, H., (1989) 'OPCS Surveys of disability in Great Britain', Report 4: Disabled Adults: Services, Transport and Employment, HMSO.
82. Mason, C.P. and Peizer, E., (1978) 'Medical manipulator for quadriplegics', International Conference on Telemanipulators for the Physically Handicapped. Rocquencourt, France, Sept 4-6, pp.309-318.
83. Massey, B.S., (1984) Mechanics of Fluids, (Wokingham, Van Nostrand Reinhold).
84. Matthews, R., (1987) 'Slave to the market', Design, January, pp.30-31.
85. Middendorf, W.H., (1986) 'Decisions', In: Design of Devices and Systems, (New York, Dekker), pp.198-230.
86. Mortimer, J., (ed) (1991) Robotics Newsletter, International Federation of Robotics, No.2, December, p.6.
87. N-Nagy, F. and Siegler, A., (1987) Engineering Foundations of Robotics, (London, Prentice-Hall International).
88. Pal, S.K., (1991) 'Direct drive high energy permanent magnet brush and brushless dc motors for robotic applications', IEE Colloquium on Robot actuators, Digest No. 1991/146, London, 7 October, pp.12.1-12.4.
89. Pellerin, C., (1992) 'The TCAS disposable robot', Industrial Robot, 19, 4, pp.23-24.
90. Pera, (1981) 'A survey of robots and their current applications in industry', Robots & Work Handling, October, PERA Report No. 361.



91. Plettenburg, D.H., (1989) 'Electric versus pneumatic power in hand prostheses for children', Journal of Medical Engineering & Technology, 13, 1/2, Jan-April, pp.124-128.
92. Prior, S.D., (1989) 'A review of world rehabilitation robotic research', Middlesex Polytechnic Report, December, 50pp.
93. Prior, S.D. and Warner, P.R., (1990a) 'A review of world rehabilitation robotics research'. I.E.E. Colloquium on High-Tech Help for the Handicapped, London, Digest No. 1990/054, 2 April.
94. Prior, S.D., (1990b) 'An electric wheelchair mounted robotic arm - a survey of potential users'. Journal of Medical Engineering & Technology, Vol. 14, No. 4, July/August, pp.143-154.
95. Prior, S.D. and Warner, P.R., (1991a) 'Future developments in design', Proceedings of the Cambridge Workshop on Rehabilitation Robotics, 12-14 April, pp.189-190, (CUED/B-ELECT/TR82).
96. Prior, S.D., (1991b) 'Computer aided design of rehabilitation robots', Proceedings of the 6th International Conference on CAD/CAM, Robotics and Factories of the Future, August 19-22 1991, London, pp.14-19.
97. Prior, S.D., Warner, P.R., Parsons, J.T., White, A.S. and Oettinger, P., (1992a) 'A hybrid rehabilitation robotic arm for the physically disabled electric wheelchair user', Proceedings of the 1992 International Conference on Rehabilitation Robotics, 15-16 September 1992, Keele University.
98. Prior, S.D., Warner, P.R., Parsons, J.T. and Oettinger, P. (1992b) 'Design and development of an electric wheelchair-mounted robotic arm for use by people with physical disabilities', International Symposium on Robotics, Mechatronics and Manufacturing Systems '92 Kobe, 16-20 September 1992, pp.541-546, (IMACS).
99. Prior, S.D., Warner, P.R., White, A.S., Parsons, J.T. and Gill, R. (1993a) 'Actuators for rehabilitation robots', Mechatronics, Vol. 3, No. 3, Special Issue on Robot Actuators, pp.285-294.
100. Prior, S.D., (1993b) 'PhD Thesis supplementary video', 19 min, Middlesex University.

101. Pu, J., Weston, R.H. and Liu, Y.M., (1993) 'Regional motion control models for single-axis pneumatic robots', In: Robotics : Applied Mathematics and Computational Aspects, edited by K. Warwick, Institute of Mathematics and its Applications Conference Series No.41 (London, Clarendon Press, February), pp.581-596.
102. Pullin, G., (1991) 'The importance of aesthetics in the design of rehabilitation robots', Proceedings of the International Conference on Rehabilitation Robotics, Atlanta, Georgia, June 19-20, pp.124-133.
103. Purdue, D.R., Wood, D. and Townsley, M.J., (1969) 'The design of pneumatic circuits', Fluid Power International, 34, 401, 36, pp.27-31.
104. Rahman, T., Ouerfelli, M., Stroud, S., Grove, T. and Harwin, W., (1992) 'Rehabilitation robotics at the A.I. duPont institute', Proceedings of the International Conference on Rehabilitation Robotics, Keele University, Sept 15-16.
105. Ramey, R.L., Aylor, J.H. and Johnson, B.W., (1980) 'A wheelchair-mounted manipulator controller', Proceedings of the Region 3 Conference Southeastcon, Nashville, Tennessee, pp.272-274.
106. Rivin, E.I., (1988) Mechanical Design of Robots, (London, McGraw-Hill).
107. Saito, Y., (1993) 'Present conditions and problems of vocational supporting robot', Journal of the Robotics Society of Japan: Special Issue on Robotics for Aging Society, Vol. 11, No. 5, pp.39-43 (in Japanese).
108. Sanville, F.E., (1971) 'A new method of specifying the flow-capacity of pneumatic fluid power valves', Proceedings of the Second International Fluid Power Symposium, Guildford, 4-7 January, paper D3, pp.37-47.
109. Schilling, R.J., (1990) Fundamentals of Robotics : Analysis and Control, (London, Prentice-Hall International).
110. Schodt, F.L., (1990) Inside the Robot Kingdom : Japan, Mechatronics, and the Coming Robotopia, (Tokyo, Kodansha International Ltd).
111. Schulte, H.F., (1961) 'The characteristics of the McKibben artificial muscle', The Application of External Power in Prosthetics and Orthotics, Appendix H, Publ. 874, (National Academy of Sciences, Washington, D.C.), pp.94-115.

112. Segedy, A., (1991) 'Wheelchair Focus' - A supplement to Homecare, May, pp.42-47.
113. Snyder, W.E., (1985) Industrial Robots : Computer Interfacing and Control, (London, Prentice-Hall International).
114. Takamori, T., (1991) 'Actuators of the future for robotics and mechatronics', Proceedings of the 6th International conference on Cad/Cam, robotics and Factories of the Future, Vol. II, August, pp.865-870.
115. Taylor, H.J., (1978) 'Development of two wheelchair manipulator systems', The International Conference on Telemanipulators for the Physically Handicapped, Rocquencourt, France, Sept 4-6 pp.117-132.
116. Tillett, N.D., (1993) 'Flexible pneumatic actuators for horticultural robots - A feasibility study', Mechatronics, Vol. 3, No. 3, Special Issue on Robot Actuators, pp.315-328.
117. Todd, S.P., (1990) 'Choosing a wheelchair', Journal of Rehabilitation Research & Development, Clinical Supplement #2, October.
118. Topping, M.J., (1992) 'Some early experience gained in the placement of 'Handy 1' robotic aid to eating', Proceedings of the International Conference on Rehabilitation Robotics, Keele University, Sept 15-16.
119. Uno, M. and Sakaguchi, Y., (1969) 'Development of a robot arm using the rubberuator' (in Japanese), Proceedings of the 2nd Annual Conference of the Robotics Society of Japan, pp.163-164.
120. Valettas, N., Goldenberg, A.A. and Milner, M. (1988) 'Development of a robotic aid for the high level quadriplegic : work in progress', Proceedings of the Joint Coordinating Forum for the International Advanced Robotics Programme, National Research Council of Canada, Ottawa, Ontario, pp.11.1-11.10.
121. Van der loos, H.F.M., Michalowski, S., Hammel, J., Leifer, L and Stassen, H., (1988) 'Assessing the impact of robotic devices for the severely physically disabled', Proceedings of the 1st International Workshop on Robotic Applications In Medical & Healthcare, Joint Coordinating Forum for The International Advanced Robotics Programme (I.A.R.P.), pp.1.1-1.6.

122. Whitehead, R.W., (1991) 'Electric motors; characteristics and applications', In: Kempe's Engineers Year-Book, edited by C. Sharpe, (London, Morgan-Grampian), pp.G4/1-G4/28.
123. Wilkie, D.R., (1960) 'Man as a source of mechanical power', Ergonomics, Vol. 3, pp.1-8.
124. Winters, J.M., Stark, L. and Seif-Naraghi, A., (1988) 'An analysis of the sources of musculoskeletal system impedance', Journal of Biomechanics, Vol. 21, No. 12, pp.1011-1025.
125. Winters, J.M., (1990) 'Braided artificial muscles : Mechanical properties and future uses in prosthetics/orthotics', Proceedings of the 13th Annual RESNA Conference, Washington, D.C., June 15-20, pp.173-174.
126. Woodson, W.E., (1981) Human Factors Design Handbook, (New York, McGraw-Hill Book Company).
127. Young, J.F., (1971) 'Power for actuation', In: Robotics, (London, Butterworths), pp.72-90.
128. Zeelenberg, A.P., (1986) 'Domestic use of a training robot-manipulator by children with muscular dystrophy', In: Monograph 37: Interactive Robotic Aids - One Option for Independent Living : An International Perspective, (New York, World Rehabilitation Fund), pp.29-33.



**APPENDIX A : MIDDLESEX QUESTIONNAIRE SURVEY**

---

ROBOTIC AID QUESTIONNAIRE

(please ring/tick the appropriate word/box)  
 (or if question does not apply please leave blank)

FEBRUARY 1989: MIDDLESEX POLYTECHNIC  
 (MK VIII)

\*\*\*\*\*  
 ROBOTIC AID RESEARCH QUESTIONNAIRE  
 \*\*\*\*\*

NAME: (OPTIONAL) \_\_\_\_\_

AGE GROUP: UNDER 16 16-25 26-35 36-45 46-55 56-65 66-75 75+

SEX: MALE FEMALE

MARITAL STATUS: MARRIED SINGLE WIDOW/ER DIVORCED/SEPARATED

ACCOMMODATION: HOME HOSPITAL INSTITUTION

IF AT HOME, ARE YOU ? ALONE WITH A PARTNER WITH FAMILY

IF AT HOME, DO YOU HAVE ANY HOME HELP ? YES NO

EMPLOYMENT: FULL-TIME PART-TIME OCCASIONALLY NONE

OCCUPATION: \_\_\_\_\_

PASTIMES: 0 1-3 4-6 7-9 10-12 13-15 16+ (AVERAGE HRS/DAY)

TELEVISION  
 READING  
 RADIO  
 HIFI  
 CITIZEN'S BAND RADIO  
 STAMP COLLECTING  
 BOARD GAMES  
 COMPUTER GAMES  
 OTHERS:  
 (NAME THEM)

|  |  |  |  |  |  |  |  |
|--|--|--|--|--|--|--|--|
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |

DISABILITY: \_\_\_\_\_

LESION LEVEL: C1-C2 C3 C4 C5 C6 C7 C8-T1 T2-T8 T8-T12 L1-L5-S1 S2 & BELOW  
 (IF APPLICABLE)

LEVEL OF DISABILITY: COMPLETE INCOMPLETE INVOLUNTARY MOVEMENTS

PART OF BODY TOTAL PARTIAL NONE

|            |  |  |  |  |
|------------|--|--|--|--|
| HEAD       |  |  |  |  |
| RIGHT ARM  |  |  |  |  |
| LEFT ARM   |  |  |  |  |
| RIGHT HAND |  |  |  |  |
| LEFT HAND  |  |  |  |  |
| RIGHT LEG  |  |  |  |  |
| LEFT LEG   |  |  |  |  |

ROBOTIC AID QUESTIONNAIRE

(please ring/tick the appropriate word/box)  
 (or if question does not apply please leave blank)

POSSIBLE TASKS OF A ROBOTIC AID:

HOW WELL CAN YOU PERFORM THE FOLLOWING TASKS ?

PERSONAL HYGIENE TASKS:                      WELL    WITH DIFFICULTY    WITH AN AID    NOT AT ALL

|                         | WELL | WITH DIFFICULTY | WITH AN AID | NOT AT ALL |
|-------------------------|------|-----------------|-------------|------------|
| BRUSHING TEETH          |      |                 |             |            |
| WASHING FACE            |      |                 |             |            |
| COMBING HAIR            |      |                 |             |            |
| BLOWING NOSE            |      |                 |             |            |
| SHAVING/MAKE UP         |      |                 |             |            |
| SCRATCHING ONESELF      |      |                 |             |            |
| WASHING HANDS           |      |                 |             |            |
| WASHING HAIR            |      |                 |             |            |
| <u>TOILETRY DUTIES:</u> |      |                 |             |            |
| CLEANING AFTER TOILET   |      |                 |             |            |
| REARRANGING CLOTHES     |      |                 |             |            |
| CHANGING LEG BAG        |      |                 |             |            |
| EMPTYING LEG BAG        |      |                 |             |            |
| ANY OTHER TASKS: _____  |      |                 |             |            |
| (NAME THEM) _____       |      |                 |             |            |

DOMESTIC TASKS:

|                              |  |  |  |  |
|------------------------------|--|--|--|--|
| COOKING                      |  |  |  |  |
| PREPARING FOOD               |  |  |  |  |
| <u>MAKING A HOT DRINK:</u>   |  |  |  |  |
| FILLING THE KETTLE           |  |  |  |  |
| SWITCHING IT ON/OFF          |  |  |  |  |
| PREPARING UTENSILS           |  |  |  |  |
| POURING WATER/MILK           |  |  |  |  |
| ADDING SUGAR                 |  |  |  |  |
| STIRRING                     |  |  |  |  |
| <u>EATING: USING A KNIFE</u> |  |  |  |  |
| USING A FORK                 |  |  |  |  |
| USING A SPOON                |  |  |  |  |
| DRINKING                     |  |  |  |  |
| PICKING & PLACING OBJECTS    |  |  |  |  |
| DUSTING/WIPING               |  |  |  |  |
| HOOVERING                    |  |  |  |  |
| OPENING FOOD CANS            |  |  |  |  |
| OPERATING TAPS               |  |  |  |  |
| USING SINK PLUGS             |  |  |  |  |
| OPERATING SWITCHES           |  |  |  |  |
| OPENING/CLOSING DOORS        |  |  |  |  |
| OPERATING LIGHT SWITCHES     |  |  |  |  |
| OPENING/CLOSING WINDOWS      |  |  |  |  |
| OPENING/CLOSING CURTAINS     |  |  |  |  |
| ANY OTHER TASKS: _____       |  |  |  |  |
| (NAME THEM) _____            |  |  |  |  |

ROBOTIC AID QUESTIONNAIRE

[please ring/tick the appropriate word/box]  
 [or if question does not apply please leave blank]

LEISURE/RECREATION TASKS: WELL WITH DIFFICULTY WITH AN AID NOT AT ALL

|                           |  |  |  |
|---------------------------|--|--|--|
| READING A BOOK            |  |  |  |
| READING A NEWSPAPER       |  |  |  |
| READING A MAGAZINE        |  |  |  |
| PLAYING COMPUTER GAMES    |  |  |  |
| PLAYING ON FRUIT MACHINES |  |  |  |
| OPERATING TELEVISION      |  |  |  |
| OPERATING RADIO           |  |  |  |
| OPERATING RECORD PLAYER   |  |  |  |
| OPERATING CASSETTE PLAYER |  |  |  |
| OPERATING COMPACT DISC    |  |  |  |
| OPERATING VIDEO RECORDER  |  |  |  |
| SMOKING                   |  |  |  |
| DRAWING/PAINTING          |  |  |  |
| OPENING WINE BOTTLES      |  |  |  |
| PICK UP & THROW OBJECTS   |  |  |  |
| PLAYING SNOOKER           |  |  |  |
| PLAYING BOWLS             |  |  |  |
| PLAYING CHESS             |  |  |  |
| GARDENING                 |  |  |  |
| SHOOTING                  |  |  |  |
| FISHING                   |  |  |  |
| ANY OTHER TASKS: _____    |  |  |  |
| (NAME THEM)               |  |  |  |

WORKING ENVIRONMENT TASKS:

|                               |  |  |  |
|-------------------------------|--|--|--|
| USING A WORD PROCESSOR        |  |  |  |
| TYPING                        |  |  |  |
| PICK & PLACE OBJECTS          |  |  |  |
| USING A COMPUTER              |  |  |  |
| INSERTING FLOPPY DISCS        |  |  |  |
| PREPARING DOCUMENTS           |  |  |  |
| USING A STAPLER               |  |  |  |
| ANSWERING THE PHONE           |  |  |  |
| DIALING THE PHONE             |  |  |  |
| OPERATING A TAPE RECORDER     |  |  |  |
| USING A PHOTOCOPIER           |  |  |  |
| OPERATING A FAX MACHINE       |  |  |  |
| OPENING A LETTER              |  |  |  |
| READING A LETTER              |  |  |  |
| PLACE A LETTER IN AN ENVELOPE |  |  |  |
| SEALING AN ENVELOPE           |  |  |  |
| STAMPING AN ENVELOPE          |  |  |  |
| POSTING AN ENVELOPE           |  |  |  |
| USING A CALCULATOR            |  |  |  |
| FILING DOCUMENTS              |  |  |  |
| ANY OTHER TASKS: _____        |  |  |  |
| (NAME THEM)                   |  |  |  |



ROBOTIC AID QUESTIONNAIRE

[please ring/tick the appropriate word/box]

[or if question does not apply please leave blank]

PLEASE LIST THE TOP FIVE TASKS THAT YOU WOULD MOST LIKE TO DO BUT CANNOT ?

1. \_\_\_\_\_
2. \_\_\_\_\_
3. \_\_\_\_\_
4. \_\_\_\_\_
5. \_\_\_\_\_

IF A DEVICE COULD DO SOME OF THE ABOVE WOULD YOU CONSIDER BUYING IT ?

YES      NO

INPUT DEVICE FAMILIARITY:

TYPE OF INPUT DEVICE:                      FAMILIAR      USED      UNFAMILIAR      NEVER USED

|                       |  |  |  |  |
|-----------------------|--|--|--|--|
| SUCK-BLOW SWITCHES    |  |  |  |  |
| JOYSTICK              |  |  |  |  |
| REMOTE CONTROL UNIT   |  |  |  |  |
| HEAD MOVEMENT SENSOR  |  |  |  |  |
| ROLLERBALL CONTROL    |  |  |  |  |
| CHIN OPERATED CONTROL |  |  |  |  |
| EYE MOVEMENT CONTROL  |  |  |  |  |
| ULTRASONIC SENSOR     |  |  |  |  |
| VOICE ACTIVATED       |  |  |  |  |

WOULD YOU BE WILLING TO TAKE PART IN A FUTURE PRACTICAL TRIAL STAGE ?

YES      NO

IF YES, PLEASE GIVE CONTACT ADDRESS.

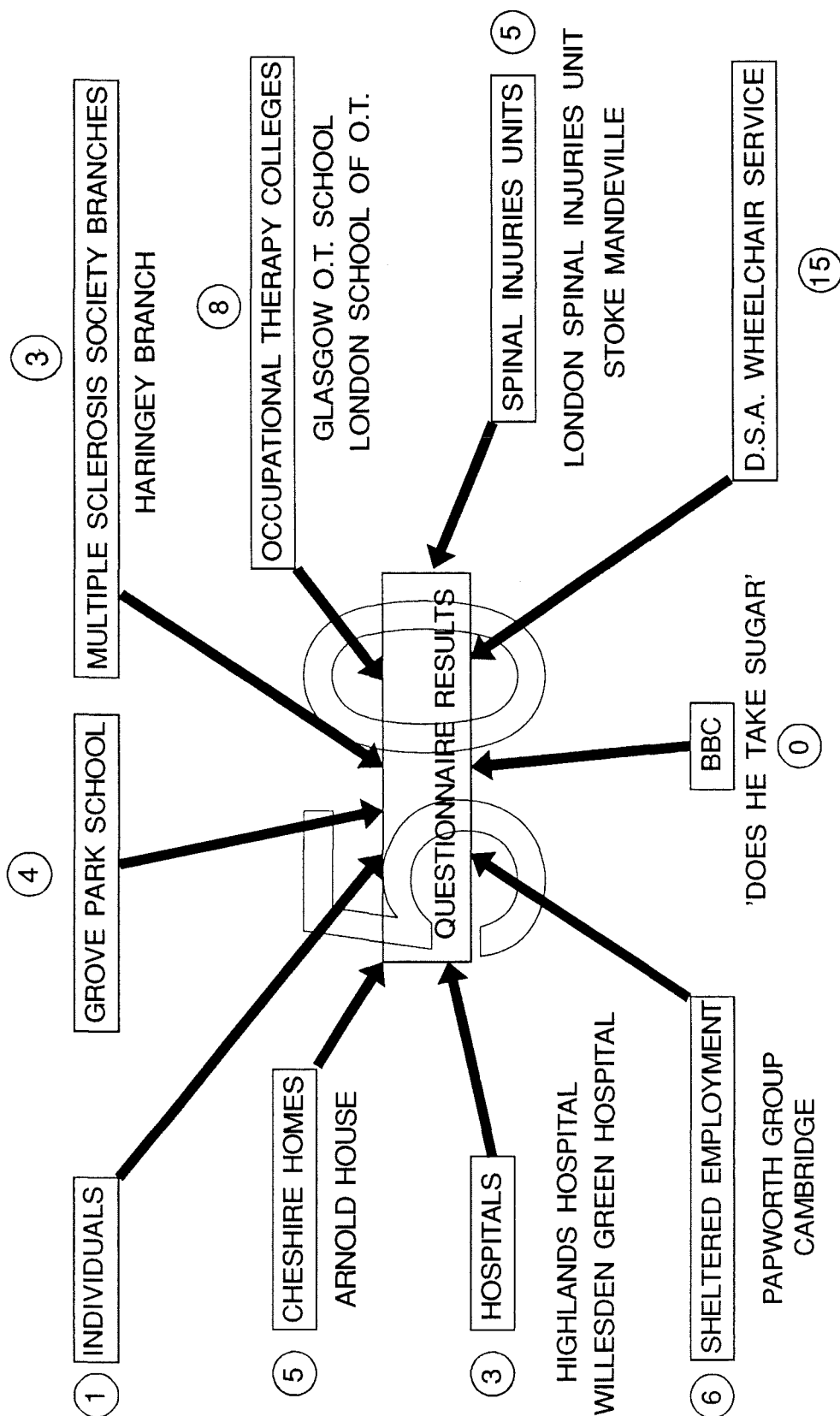
\_\_\_\_\_

\_\_\_\_\_


\_\_\_\_\_

\_\_\_\_\_

\*\*\*\*\*  
 THANK YOU FOR YOUR TIME AND PATIENCE  
 \*\*\*\*\*



NUMBERS INDICATE COMPLETED QUESTIONNAIRES



**APPENDIX B1 : COMPARISON OF PNEUMATIC & HYDRAULIC ROTARY  
DIRECT-DRIVE ACTUATORS**

---

| Method of Actuation                          | Actuator Type                        | Dimensions (mm) |       |        | Mass (kg) | Peak Torque (Nm) @ 6 bar | Tp/MM Ratio (Nm/kg) | Cost (Ex VAT) (£) |
|--|--------------------------------------|-----------------|-------|--------|-----------|--------------------------|---------------------|-------------------|
|  |                                      | Height          | Width | Length |           |                          |                     |                   |
| Pneumatic (Festo) DSRL Series ø16            | Single Vane 0° to 184° Hollow Shaft  | 57              | 78    | 76     | 0.310     | 2                        | 6.451               | 117.66            |
| ø25  | "                                    | 68              | 98    | 95     | 0.540     | 5                        | 9.259               | 127.31            |
| ø32  | "                                    | 92              | 130   | 126    | 1.285     | 10                       | 7.782               | 158.83            |
| ø40  | "                                    | 121             | 160   | 162    | 2.400     | 20                       | 8.333               | 199.96            |
| Pneumatic (Kinetro) OMO-100                  | Single Vane 80° to 100° (Adjustable) | 30.7            | 32    | 56     | 0.12      | 0.8                      | 6.666               | 32.46             |
| 010-100A                                     | 78° to 100°                          | 57.3            | 71.4  | 58     | 0.25      | 5.6                      | 22.4                | 40.17             |
| 020-100                                      | 80° to 96°                           | 76              | 93    | 70     | 0.44      | 10.2                     | 23.182              | 41.97             |
| 050-100                                      | 83° to 100°                          | 111.5           | 136   | 93     | 1.28      | 42.9                     | 33.516              | 71.08             |
| 090-100                                      | 80° to 100°                          | 186             | 226   | 178    | 6.54      | 220                      | 33.639              | 127.60            |
| 120-100                                      | 80° to 102°                          | 235             | 294   | 218    | 12.5      | 490                      | 39.2                | 210.43            |
| 160-100                                      | 80° to 100°                          | 425             | 525   | 384    | 39.8      | 2659                     | 66.81               | 1089.82           |
| 180-100                                      | 80° to 100°                          | 554             | 680   | 516    | 77.6      | 5948                     | 76.649              | 2361.52           |
| Pneumatic (Parker/Schrader Bellows) Model 10 | Double Vane 95°                      | 41              | 41    | 61.3   | 0.17      | 1.47                     | 8.647               | 83.17             |
| 11   | "                                    | 41              | 41    | 77.3   | 0.23      | 3.05                     | 13.261              | 89.11             |
| 22   | 100°                                 | 63.5            | 63.5  | 110    | 0.8       | 13.27                    | 16.588              | 121.35            |
| 32   | "                                    | 76              | 76    | 157    | 1.62      | 30.96                    | 19.111              | 169.05            |

| Method of Actuation                       | Actuator Type              | Dimensions (mm) |       |        | Mass (kg) | Peak Torque (Nm) @ 6 bar | T <sub>p</sub> /MM Ratio (Nm/kg) | Cost (Ex VAT) (£) |
|---|----------------------------|-----------------|-------|--------|-----------|--------------------------|----------------------------------|-------------------|
|   |                            | Height          | Width | Length |           |                          |                                  |                   |
| Pneumatic (CompAir Maxam) Hi-Rotor PRN001 | Single Vane 90° or 180°+4° | 30              | 30    | 45     | 0.035     | 0.13                     | 3.714                            | 52.20             |
| 003                                       | "                          | 37              | 37    | 55     | 0.07      | 0.36                     | 5.143                            | 55.70             |
| 010                                       | "                          | 42              | 42    | 77     | 0.16      | 1.15                     | 7.188                            | 67.80             |
| 020A                                      | " +3°                      | ∅ 49            | /     | 100    | 0.36      | 1.95                     | 5.417                            | 112.50            |
| 030S                                      | 90°, 180° or 270°+3°       | 64              | 64    | 105    | 0.47      | 4                        | 8.511                            | 120.90            |
| 050S                                      | 180° or 280° +3°           | ∅ 79            | /     | 145    | 0.79-0.7  | 5.9                      | 7.468-8.429                      | 132.90            |
| 150S                                      | "                          | ∅ 110           | /     | 180    | 1.9-1.6   | 18                       | 9.474-11.25                      | 190.80            |
| 300S                                      | "                          | ∅ 141.5         | /     | 220    | 3.7-3.6   | 34.5                     | 9.324-9.583                      | 301.80            |
| 800S                                      | "                          | ∅ 196           | /     | 285    | 12.2-11.0 | 123.3                    | 10.107-11.21                     | 522.40            |
| 050D                                      | Double Vane 90° or 100°+3° | ∅ 79            | /     | 145    | 0.82-0.8  | 12.8                     | 15.61-16                         | 176.00            |
| 150D                                      | "                          | ∅ 110           | /     | 180    | 2.0-1.9   | 41.5                     | 20.75-21.842                     | 250.30            |
| 300D                                      | "                          | ∅ 141.5         | /     | 220    | 4.3-4.1   | 83                       | 19.302-20.244                    | 392.20            |
| 800D                                      | "                          | ∅ 196           | /     | 285    | 12.7-12.5 | 246.5                    | 19.409-19.72                     | 662.70            |
| Pneumatic (Tol-O-Matic) 1810-0200         | Double Vane 0° to 100°     | 38.1            | 38.1  | 86.1   | 0.198     | 3.38                     | 17.071                           | 110.93            |


| Method of Actuation        | Actuator Type                   | Dimensions (mm) |       |        | Mass (kg) | Peak Torque (Nm) @ 6 bar | T <sub>p</sub> /MM Ratio (Nm/kg) | Cost (Ex VAT) (£) |
|----------------------------|---------------------------------|-----------------|-------|--------|-----------|--------------------------|----------------------------------|-------------------|
|                            |                                 | Height          | Width | Length |           |                          |                                  |                   |
| 1810-0201                  | Single Vane<br>0° to 280°       | 38.1            | 38.1  | 86.1   | 0.198     | 1.69                     | 8.535                            | 104.72            |
| 1817-0200                  | Double Vane<br>0° to 100°       | 63.5            | 63.5  | 133.4  | 0.909     | 16.28                    | 17.91                            | 172.41            |
| 1817-0201                  | Single Vane<br>0° to 280°       | 63.5            | 63.5  | 133.4  | 0.909     | 8.14                     | 8.955                            | 171.02            |
| 1825-0001                  | Double Vane<br>0° to 100°       | 76.2            | 76.2  | 158.75 | 1.9       | 31.18                    | 16.411                           | 227.32            |
| 1825-0002                  | Single Vane<br>0° to 280°       | 76.2            | 76.2  | 158.75 | 1.9       | 15.59                    | 8.205                            | 225.92            |
| Pneumatic (Rotac) LP-11-2V | Double Vane<br>90°±1°           | 52.32           | 52.32 | 80.77  | 0.28      | 2.55                     | 9.107                            | 188.00            |
| 22-2V                      | "                               | 77.72           | 77.72 | 133.35 | 1.00      | 12.66                    | 12.66                            | 258.00            |
| 11-1V                      | Single Vane<br>270°±1°          | 52.32           | 52.32 | 80.77  | 0.26      | 1.02                     | 3.923                            | 167.00            |
| 22-1V                      | "                               | 77.72           | 77.72 | 133.35 | 0.96      | 5.54                     | 5.771                            | 237.00            |
| Pneumatic (SMC) CRA1-BW30  | Single Rack & Pinion<br>180°±3° | 75              | 45    | 103    | 0.041     | 0.25                     | 6.098                            | 126.73            |
| BS50                       | " +4°                           | 98              | 62    | 177    | 0.173     | 1.15                     | 6.647                            | 187.63            |
| BS63                       | "                               | 117             | 76    | 201.5  | 0.306     | 2.0                      | 6.536                            | 234.25            |
| BS80                       | "                               | 142             | 92    | 230    | 0.509     | 3.5                      | 6.876                            | 289.79            |
| BS100                      | "                               | 172             | 112   | 311    | 0.968     | 9.0                      | 9.298                            | 458.13            |
| Pneumatic (SMC) CRB1-BW10  | Single Vane<br>180°+5°          | ∅ 29            | /     | 37     | 0.003     | 0.014                    | 4.667                            | 62.77             |

| Method of Actuation                        | Actuator Type                | Dimensions (mm) |       |        | Mass (kg) | Peak Torque (Nm) @ 6 bar | T <sub>p</sub> /MM Ratio (Nm/kg) | Cost (Ex VAT) (£) |
|--|------------------------------|-----------------|-------|--------|-----------|--------------------------|----------------------------------|-------------------|
|  |                              | Height          | Width | Length |           |                          |                                  |                   |
| BW15                                       | " +4°                        | ø 34            | /     | 47     | 0.005     | 0.038                    | 7.6                              | 64.69             |
| BW20                                       | " +4°                        | ø 42            | /     | 59     | 0.011     | 0.085                    | 7.727                            | 66.98             |
| BW30                                       | " +4°                        | ø 50            | /     | 75     | 0.020     | 0.22                     | 11                               | 70.00             |
| Pneumatic (Kuhnke) (Kuax) 701.010          | Double Acting Piston 90° +5° | 35              | 35    | 77.5   | 0.3       | 0.55                     | 1.833                            | 96.30             |
| 701.000                                    | "                            | 50              | 50    | 112.5  | 0.9       | 1.35                     | 1.5                              | 145.81            |
| Pneumatic (Parker/Schrader Bellows) SR 101 | Single Rack & Pinion 180°    | 73              | 76    | 210    | 1.25      | 3.84                     | 3.072                            | 802.03            |
| "  | 360°                         | 73              | 76    | 291    | 1.47      | 3.84                     | 2.612                            | 829.37            |
| DR 102                                     | Double Rack & Pinion 180°    | 73              | 76    | 210    | 1.98      | 7.68                     | 3.879                            | 1002.55           |
| "  | 360°                         | 73              | 76    | 291    | 2.32      | 7.68                     | 3.310                            | 1051.15           |
| SR 201                                     | Single Rack & Pinion 180°    | 124             | 127   | 357    | 6.63      | 27.72                    | 4.181                            | 1485.58           |
| "  | 360°                         | 124             | 127   | 500    | 7.60      | 27.72                    | 3.647                            | 1576.73           |
| DR 202                                     | Double Rack & Pinion 180°    | 124             | 127   | 357    | 9.92      | 55.44                    | 5.589                            | 2090.14           |
| "  | 360°                         | 124             | 127   | 500    | 11.85     | 55.44                    | 4.678                            | 2275.46           |
| SR 321                                     | Single Rack & Pinion 180°    | 216             | 203   | 540    | 21.55     | 122.76                   | 5.697                            | 3229.40           |
| "  | 360°                         | 216             | 203   | 779    | 23.70     | 122.76                   | 5.18                             | 3451.17           |

| Method of Actuation          | Actuator Type                  | Dimensions (mm) |       |        | Mass (kg) | Peak Torque (Nm) @ 6 bar | T <sub>p</sub> /MM Ratio (Nm/kg) | Cost (Ex VAT) (£) |
|------------------------------|--------------------------------|-----------------|-------|--------|-----------|--------------------------|----------------------------------|-------------------|
|                              |                                | Height          | Width | Length |           |                          |                                  |                   |
| DR 322                       | Double Rack & Pinion 180°      | 216             | 203   | 540    | 30.62     | 245.52                   | 8.018                            | 4259.28           |
| "                            | 360°                           | 216             | 203   | 779    | 34.93     | 245.52                   | 7.029                            | 4714.98           |
| Pneumatic (El-O-Matic) ED 12 | Double Rack & Pinion 90°± 1°   | 76              | 60    | 87     | 0.6       | 15                       | 25                               | 57.20             |
| ED 25                        | "                              | 93              | 74    | 129    | 1.3       | 27                       | 20.769                           | 68.50             |
| ED 40                        | "                              | 106             | 86    | 144    | 1.8       | 51                       | 28.333                           | 89.80             |
| ED 100                       | "                              | 133             | 108   | 187    | 3.7       | 114                      | 30.811                           | 120.80            |
| ED 200                       | "                              | 158             | 128   | 200    | 6.1       | 251                      | 41.148                           | 171.20            |
| PD 50                        | 90°± 0.5°                      | 215             | 198   | 276    | 14        | 577                      | 41.214                           | 292.60            |
| PD 110                       | "                              | 285             | 260   | 340    | 30.8      | 1246                     | 40.455                           | 545.00            |
| PD 400                       | "                              | 420             | 358   | 502    | 97.8      | 4930                     | 50.512                           | 1868.00           |
| Pneumatic (Norbro) 10-40R    | Double Rack & Pinion 90°± 1.5° | 86              | 77.2  | 155.2  | 1.3       | 34.6                     | 26.615                           | 126.70            |
| 15-40R                       | "                              | 124.6           | 94.6  | 195    | 2.7       | 65                       | 24.074                           | 162.80            |
| 20-40R                       | "                              | 145.6           | 116.7 | 233.6  | 4.5       | 119                      | 26.444                           | 198.10            |
| 25-40R                       | "                              | 177.4           | 136.3 | 271    | 7.4       | 195.1                    | 26.365                           | 285.00            |
| 30-40R                       | "                              | 198.4           | 155.9 | 325.6  | 11        | 326.9                    | 29.718                           | 424.10            |
| 35-40R                       | "                              | 258.2           | 214.2 | 414.2  | 26        | 795                      | 30.577                           | 638.50            |
| 40-FK40                      | "                              | 299.4           | 244.6 | 387.1  | 31.8      | 1297                     | 40.786                           | 937.60            |



| Method of Actuation                        | Actuator Type                | Dimensions (mm) |       |        | Mass (kg) | Peak Torque (Nm) @ 6 bar | T <sub>p</sub> /MM Ratio (Nm/kg) | Cost (Ex VAT) (£) |
|--|------------------------------|-----------------|-------|--------|-----------|--------------------------|----------------------------------|-------------------|
|  |                              | Height          | Width | Length |           |                          |                                  |                   |
| 45-FK40                                    | "                            | 392.4           | 335   | 574.4  | 96.8      | 3231                     | 33.378                           | 1962.00           |
| 50-FK40                                    | "                            | 434.2           | 391   | 626    | 137.9     | 4971                     | 36.048                           | 4314.00           |
| Pneumatic (Helac Corp) PL Series Model 2.8 | Helical Planetary 0° to 180° | ∅ 151.4         | /     | 142.8  | 7         | 25                       | 3.571                            | 609.00            |
| "  | 0° to 360°                   | ∅ 151.4         | /     | 179.8  | 8.5       | 25                       | 2.941                            | 772.00            |
| Model 3.3 (Hollow Shaft)                   | 0° to 180°                   | ∅ 202.4         | /     | 165.1  | 11        | 63                       | 5.727                            | 673.00            |
| "  | 0° to 360°                   | ∅ 202.4         | /     | 211.6  | 13.5      | 63                       | 4.667                            | 854.00            |
| Model 3.8 (Hollow Shaft)                   | 0° to 180°                   | ∅ 253.2         | /     | 180.8  | 18        | 125                      | 6.944                            | 722.00            |
| "  | 0° to 360°                   | ∅ 253.2         | /     | 237.5  | 21        | 125                      | 5.952                            | 921.00            |
| Hydraulic (Hydroac) SS-.2A-1V              | Single Vane 280°±1°          | 57.15           | 57.15 | 127    | 0.727     | 1.72 (57.4 @ 210 bar)    | 2.366 (78.955 @ 210 bar)         | 1102.00           |
| HS-1.5-1V (Hollow Shaft)                   | "±5°                         | ∅ 158.75        | /     | 155.5  | 13.182    | 13.67 (455.6 @ 210 bar)  | 1.037 (34.562 @ 210 bar)         | 1226.00           |
| SS-8-1V                                    | "                            | ∅ 213.5         | /     | 296.9  | 35.455    | 71.28 (2,430 @ 210 bar)  | 2.01 (68.538 @ 210 bar)          | 1777.00           |
| SS-130-1V                                  | "                            | ∅ 520.7         | /     | 752.7  | 404.5     | 39,487.5 @ 210 bar       | 97.621 @ 210 bar                 | U/A               |
| SS-130-2V                                  | Double Vane 100°±5°          | ∅ 520.7         | /     | 752.7  | 431.8     | 83,362.5 @ 210 bar       | 193.058 @ 210 bar                | U/A               |



**APPENDIX B2 : COMPARISON OF PNEUMATIC & ELECTRIC ROTARY  
DIRECT-DRIVE ACTUATORS**


---

(Some data in this table was extracted from Asada et al, 1981)

| Class of Torque Motor | Magnet Type | Dimensions (mm) |      |        | Mass (kg) | Peak Torque (Nm) | T <sub>p</sub> /MM Ratio (Nm/kg) |
|-----------------------|-------------|-----------------|------|--------|-----------|------------------|----------------------------------|
|                       |             | O.D.            | I.D. | Length |           |                  |                                  |
| Small                 | Rare Earth  | 81              | 29   | 60     | 1.52      | 6.8              | 4.474                            |
|                       | Alnico      | 72              | 23   | 64     | 1.31      | 1.7              | 1.298                            |
| Flexator (42 x 90)    | /           | 63.5            | /    | 130    | 0.7       | 11.83 @ 6 bar    | 16.9                             |
| Medium                | Rare Earth  | 183             | 100  | 32     | 2.70      | 15.0             | 5.556                            |
|                       | Alnico      | 183             | 100  | 34     | 3.05      | 8.2              | 2.689                            |
| Flexator (102 x 130)  | /           | 63.5            | /    | 254    | 1.3       | 24.24 @ 6 bar    | 18.7                             |
| Large                 | Rare Earth  | 228             | 136  | 42     | 4.44      | 27.2             | 6.126                            |
|                       | Alnico      | 228             | 136  | 41     | 4.34      | 14.9             | 3.433                            |
| Extra Large           | Rare Earth  | 646             | 523  | 152    | 100.1     | 952              | 9.510                            |
|                       | Alnico      | 734             | 415  | 165    | 100.1     | 585              | 5.844                            |

| Motor Details                               | Actuator Type                        | Dimensions (mm) |       |        | Mass (kg) | Peak Torque (Nm)       | T <sub>p</sub> /MM Ratio (Nm/kg) | Cost (Ex VAT) (£) |
|---|--------------------------------------|-----------------|-------|--------|-----------|------------------------|----------------------------------|-------------------|
|   |                                      | Height          | Width | Length |           |                        |                                  |                   |
| (Oriental Mo. Co. Ltd)<br>Vexta<br>PH299-23 | Hybrid Stepper<br>Step Angle 1.8°    | 83              | 83    | 125.3  | 2.5       | 2.65 (Holding Torque)  | 1.06                             | 96.60             |
| "<br>PH268M-<br>EO68                        | "<br>0.9°                            | 56.4            | 56.4  | 96.6   | 0.95      | 0.833<br>"             | 0.877                            | 77.00             |
| (Kuhnke)<br>E9-95°-180V-<br>100%            | Rotary Solenoid<br>95° Spring Return | 100             | 122   | 98     | 4.5       | 1.47-1.76<br>Start-End | 0.327-<br>0.391                  | 193.18            |

| Motor Details                               | Actuator Type                                 | Dimensions (mm) |       |        | Mass (kg) | Peak Torque (Nm)       | T <sub>p</sub> /MM Ratio (Nm/kg) | Cost (Ex VAT) (£) |
|---|---|-----------------|-------|--------|-----------|------------------------|----------------------------------|-------------------|
|   |   | Height          | Width | Length |           |                        |                                  |                   |
| "<br>UD9-95°-<br>24V-100%                   | "<br>95°                                      | 100             | 125   | 202.5  | 7.6       | 0.43-0.85<br>Start-End | 0.057-<br>0.112                  | 335.81            |
| (Aerotech Ltd)<br>1010SM                    | Hybrid Stepper<br>Step Angle 1.8°             | 108             | 108   | 245.5  | 9.1       | (Holding)<br>7.4       | 0.813                            | 535.00            |
| "<br>310SM                                  | "   | 82.6            | 82.6  | 188.9  | 3.5       | "<br>2.6               | 0.743                            | 242.00            |
| "<br>1960                                   | Permanent Magnet Servo (Brushed)              | 133.4           | 133.4 | 377.4  | 16.9      | 31.7                   | 1.876                            | 638.00            |
| "<br>1580                                   | "   | 133.4           | 133.4 | 296.2  | 11.5      | 16.9                   | 1.470                            | 595.00            |
| (Norcroft)<br>(28 v)<br>11PM106             | Permanent Magnet Stepper<br>Step Angle 90°    | ∅ 27            | /     | 38     | 0.1       | (Holding)<br>0.007     | 0.07                             | 120.00            |
| "<br>(24 v)<br>20VR112                      | Variable Reluctance Stepper<br>Step Angle 15° | ∅ 51            | /     | 64     | 0.4       | "<br>0.21              | 0.525                            | 100.00            |
| "<br>(4.6 A)<br>23HB403                     | Hybrid Stepper<br>Step Angle 1.8°             | ∅ 57            | /     | 102    | 0.5       | "<br>1.0               | 2                                | 195.00            |
| "<br>(24 v)<br>23DM502                      | DC Motor (Sm Co)                              | ∅ 57            | /     | 120    | 1.0       | (Stall)<br>3.4         | 3.4                              | 515.00            |
| (HSI Inc)<br>(12 v)<br>140140-12-001        | Pancake Stepper<br>Step Angle 2°              | ∅ 171.5         | /     | 12.7   | 1.02      | (Holding)<br>0.46      | 0.451                            | 1023.75           |
| (Unimatic)<br>Sigmax<br>802-D42104<br>F2.4K | Enhanced Hybrid Stepper                       | ∅ 106.7         | /     | 264.2  | 13.3      | "<br>26.41             | 1.986                            | 880.00            |



**APPENDIX C : FLEXATOR VOLUMETRIC MEASUREMENTS**

---

## Flexator Maximum Volume Measurements ( $V_{max}$ )

The range of flexators used in this analysis were tested to find their maximum volume conditions. Due to the relatively small flows involved and the short time period over which the flow occurs, no suitable flow sensor could be found. It was therefore necessary to resort to a crude approximation technique. The results were obtained by submerging the flexators under water, with an internal flexator pressure of 0.5 bar gauge and measuring the mass of displaced water, using an electronic weighing scale. Dividing the mass of displaced water by its density, gave the total volume of the flexator. The volume of the flexator material was then deducted from the total volume to give the final volume of air in the flexator when fully inflated, under no load conditions. When a suitable sensor was eventually found the volumetric measurements of the flexators under test were rechecked, and were found to be within  $\pm 5\%$  of the original measurements.

From figure C.1 overleaf it is possible to determine the maximum volume ( $m^3$ ) of any flexator, given its length and width. The flexator's maximum volume can be accurately modelled using a 2<sup>nd</sup> order polynomial equation. However, because of the amount of variables involved it was not possible to determine a general equation governing the flexator volume for any given flexator type and torque load.

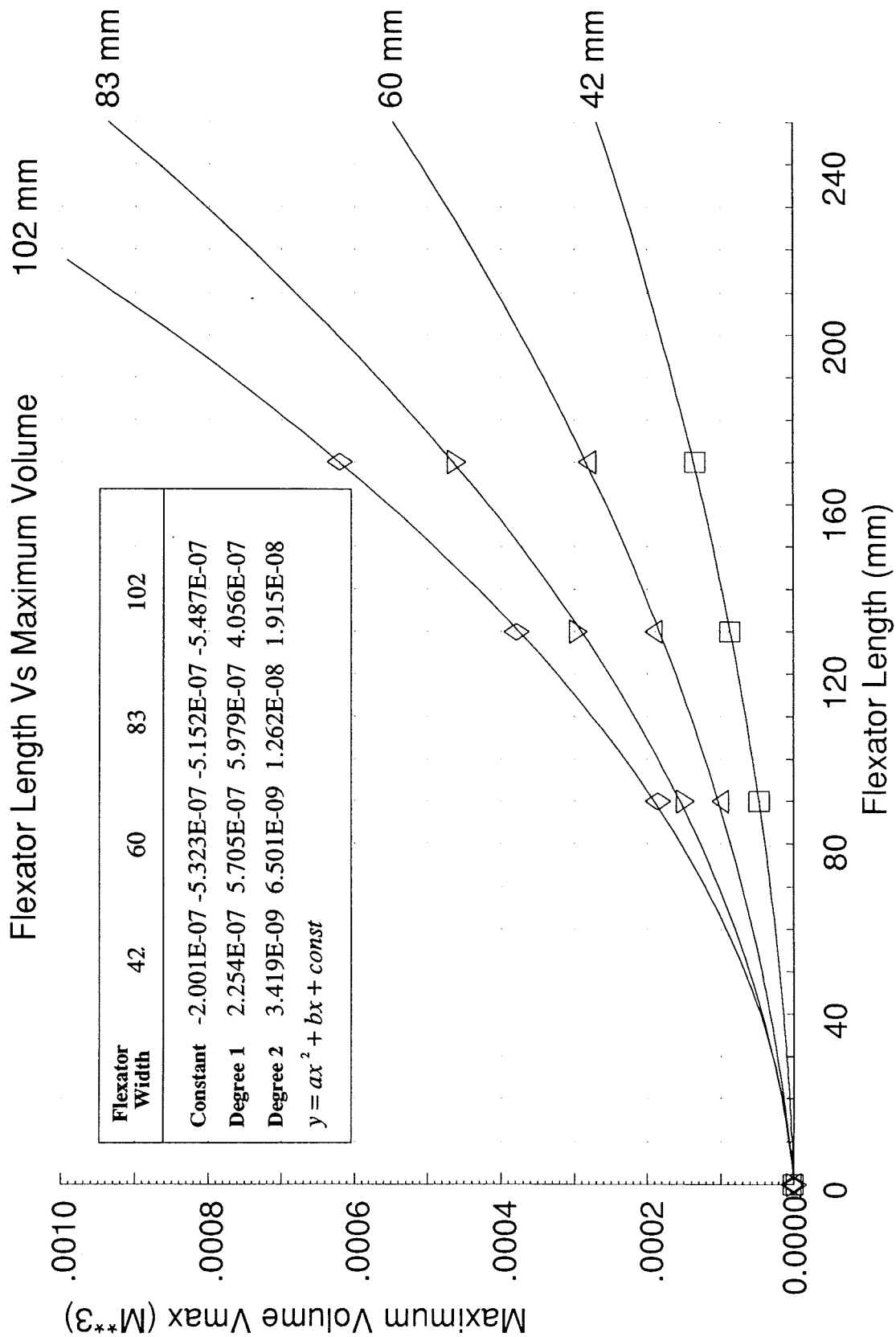
The data contained in this appendix can be used to determine whether the chosen flexator is operating near to the critical  $V_{max}$  condition (see Section 5.3.1 Limiting Conditions & Experimental Results), and can also be used to calculate the size of the reservoir required and therefore the size and operating characteristics of the compressor.

Table C.1 - Flexator Maximum Volume Analysis ( $m^3$ )

| Flat Width (mm) | 42         | 60         | 83         | 102        | Length (mm) |
|-----------------|------------|------------|------------|------------|-------------|
|                 | 4.64 E-05  | 9.98 E-05  | 15.78 E-05 | 18.73 E-05 | 90          |
| $T_L = 0$       | 8.88 E-05  | 18.86 E-05 | 29.55 E-05 | 38.11 E-05 | 130         |
|                 | 13.62 E-05 | 28.24 E-05 | 46.41 E-05 | 61.99 E-05 | 170         |

$$1 m^3 = 1000 l = 10^6 cc$$

$$Example: 62 \times 10^{-5} m^3 = 0.62 l$$

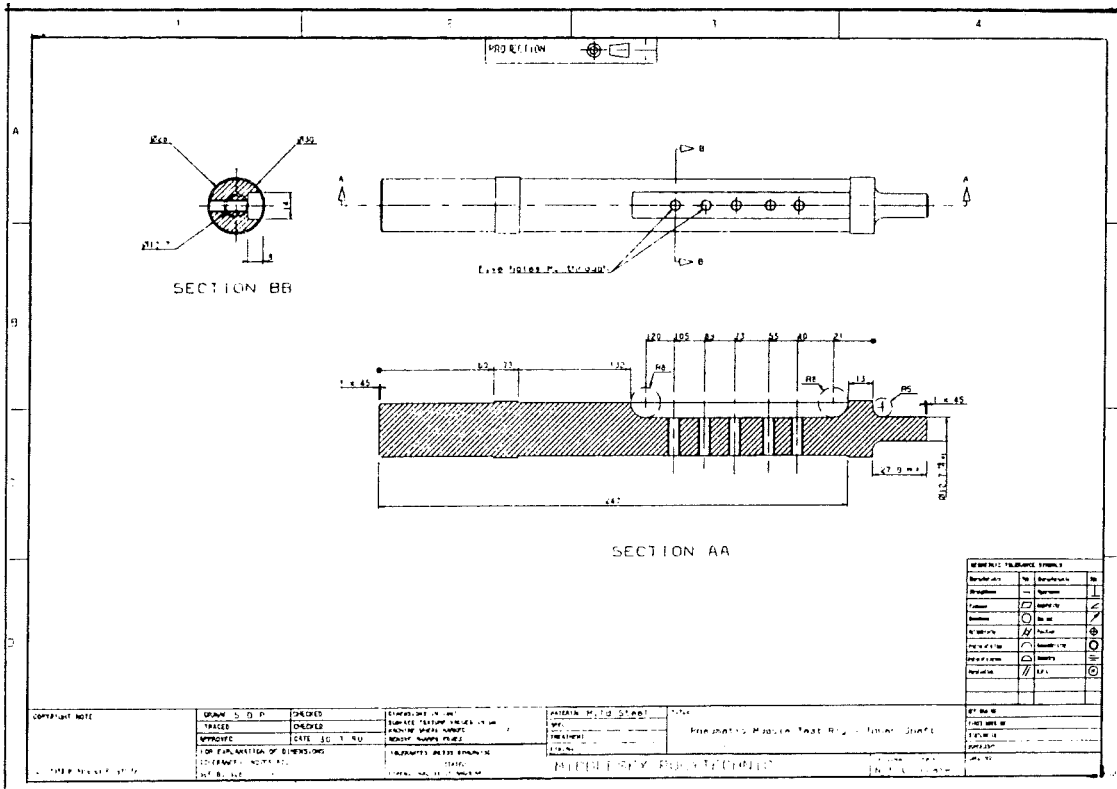
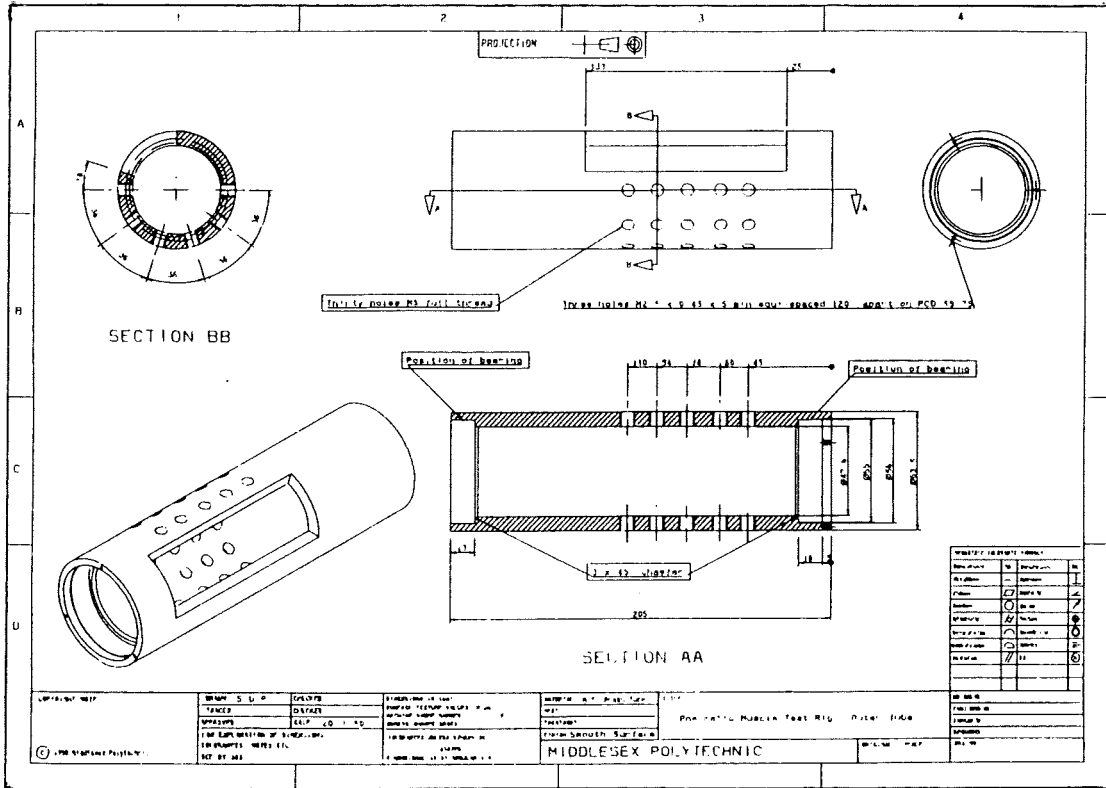




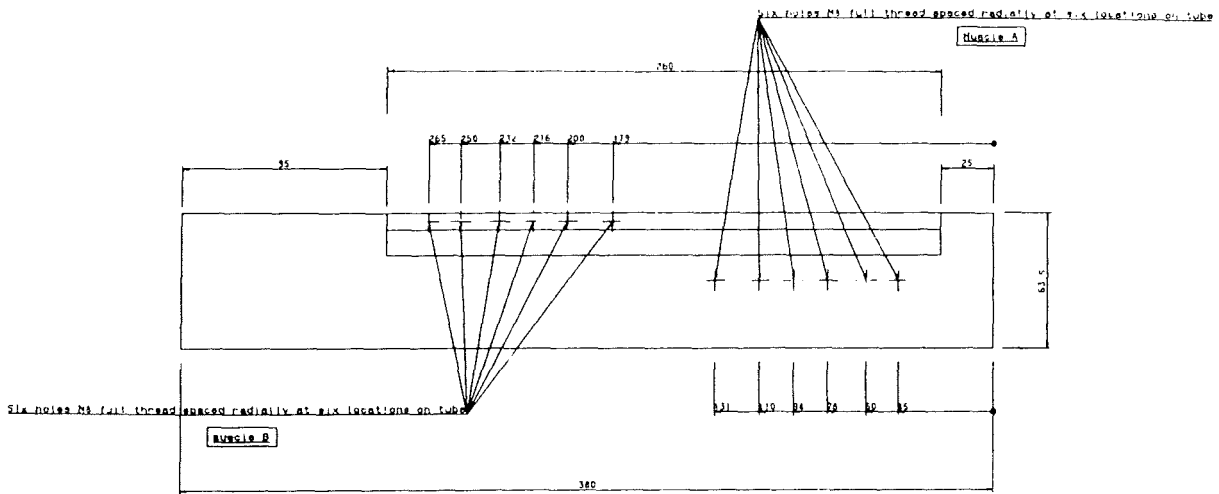
**APPENDIX D : FLEXATOR TEST-RIG WORKING DRAWINGS**

---

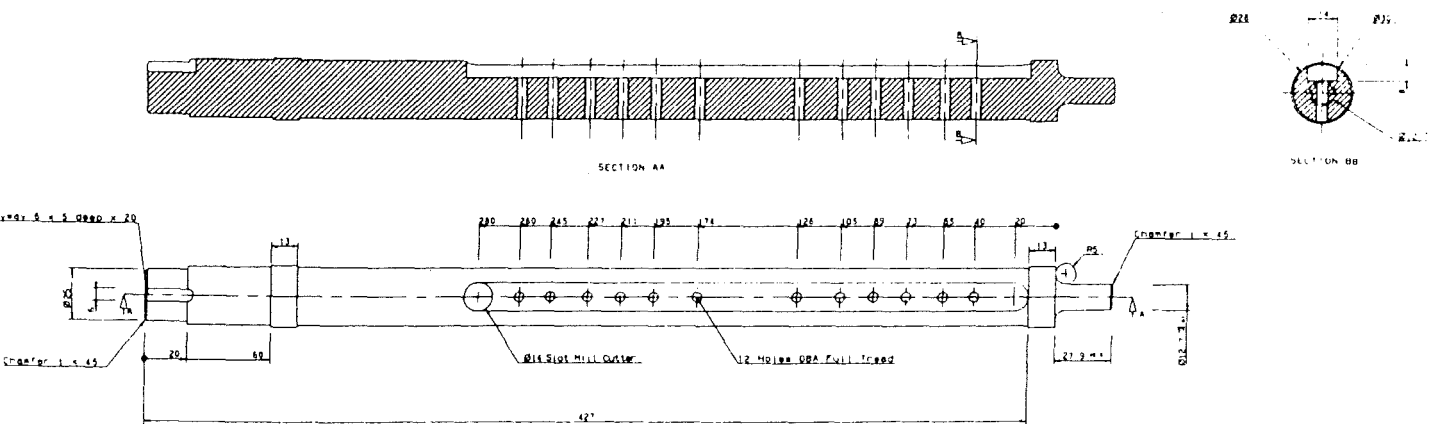




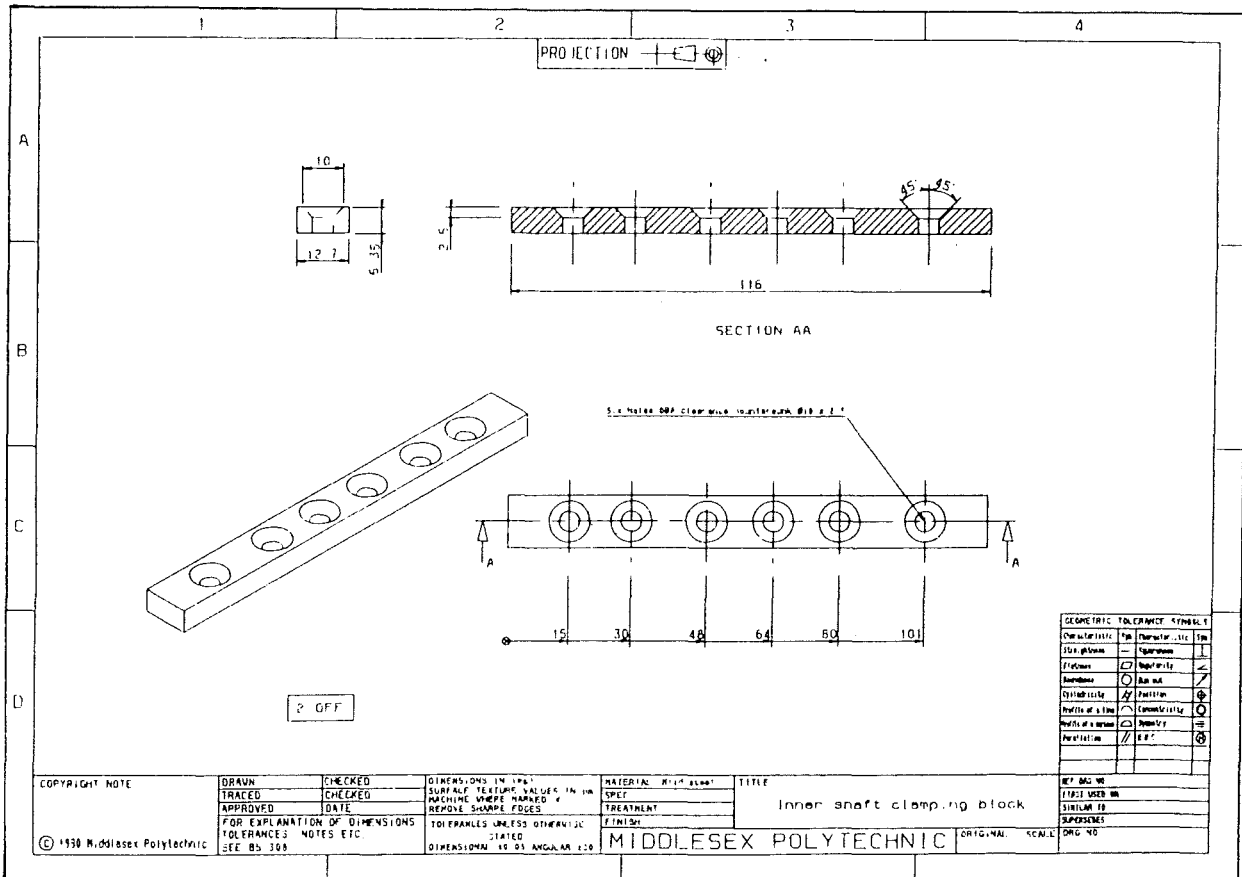
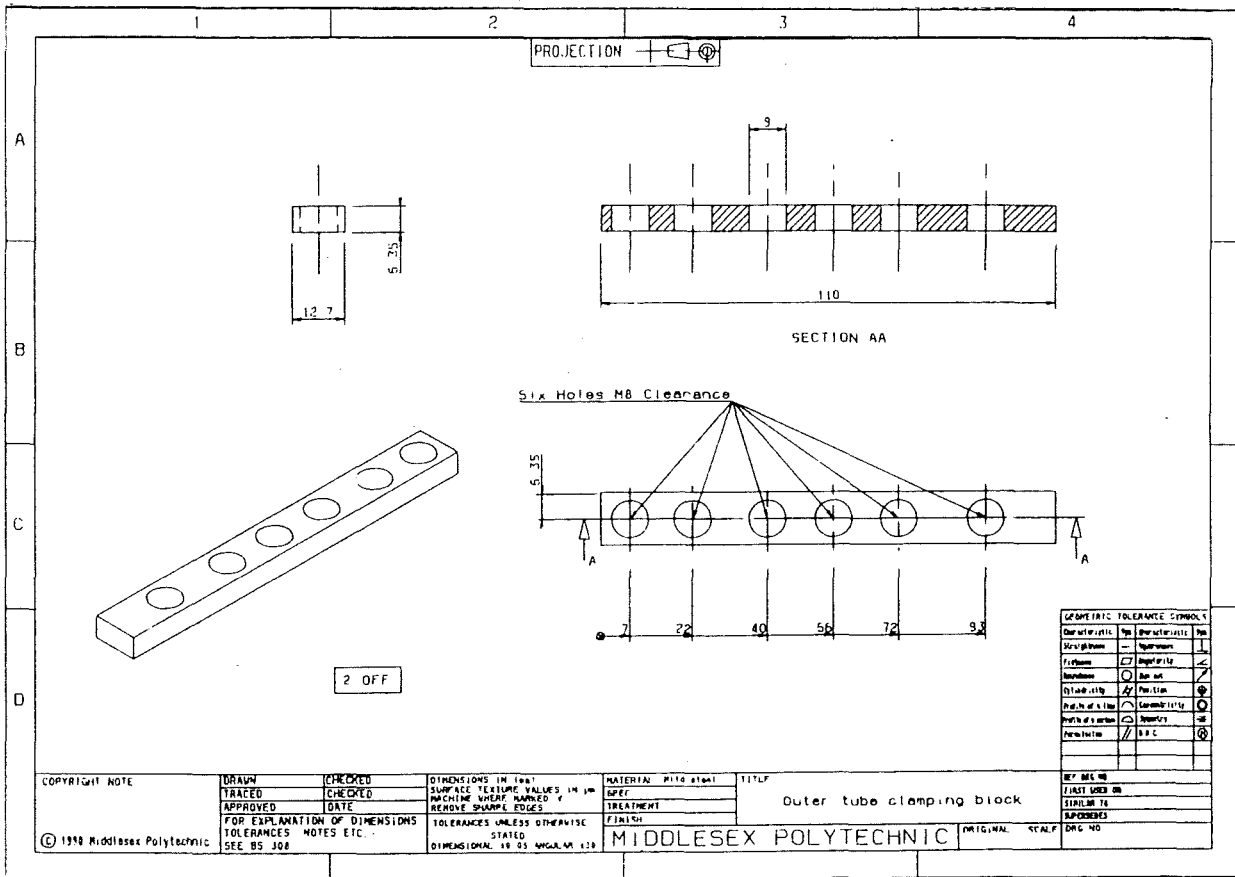
SCALE = 0.400

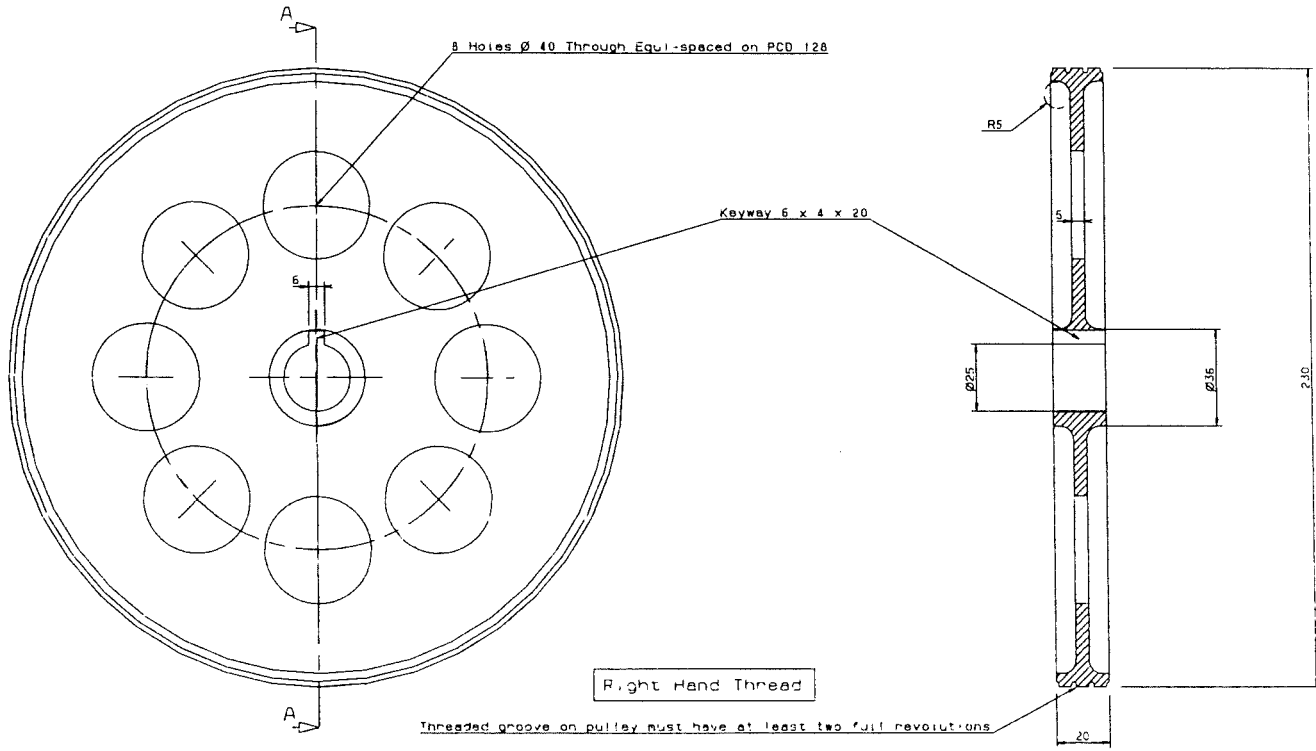


Location of muscle mounting holes from datum face of tube



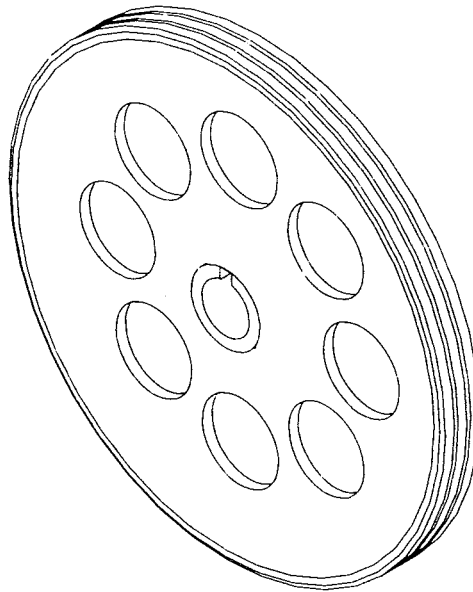
INNER SHAFT - DUAL MUSCLE SYSTEM MILD STEEL - ALL DIM IN MM





Thread pitch = 5mm. thread depth = 2mm

SECTION AA



Grooved Pulley - Dual Muscle System - Mild Steel - All Dim in MM



**APPENDIX E : FLEXATOR ACTUATOR FRICTIONAL LOSSES**

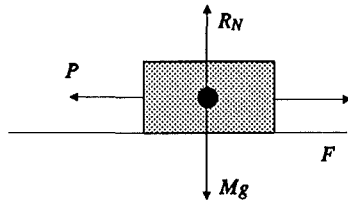
---

**Coefficient of Friction ( $\mu$ ) Tests**

Tests were carried out to analyse the frictional characteristics of the nylon webbing strap (used to restrain the flexator actuator), when it comes into contact with the PTFE strip which is fixed to the outer tube at the window edge position.

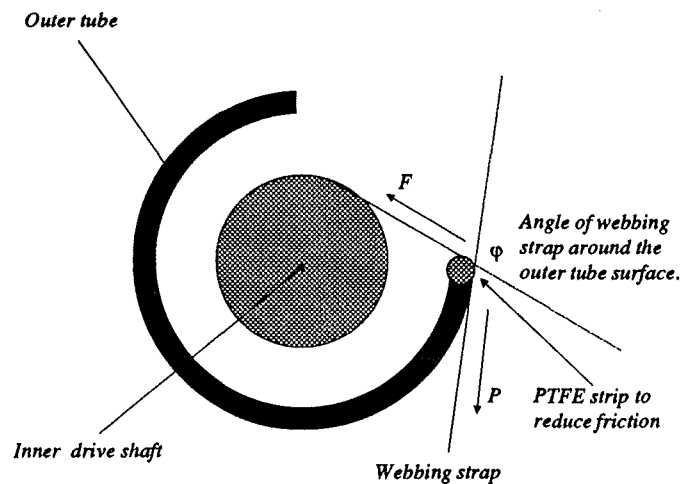
Based on the standard formula  $\mu = \frac{F}{R_N}$

Where  $F$  = Frictional Force and  $R_N$  = Normal Reaction Force.



**Table E.1 - Coefficient of Friction,  $\mu$  for Webbing Strap and PTFE Surfaces**

| Mass (kg) | (With the Grain) |         | (Against the Grain) |         |
|-----------|------------------|---------|---------------------|---------|
|           | Static           | Dynamic | Static              | Dynamic |
| 4.2       | 0.1574           | 0.1089  | 0.1453              | 0.0968  |
| 9.2       | 0.1383           | 0.0940  | 0.1328              | 0.0996  |



**Figure E.1 - Schematic of test-rig frictional contact point**

## Definition

**Woven Webbing.** A part of the sling comprising a woven narrow fabric generally of a coarse weave and multiple plies, the prime function of which is load bearing.

The specifications for flat woven webbing slings made from man-made fibres is covered by British Standards 7471, 6166, 3481 and 5759. Three widths of webbing were used during the flexator testing, these were 38mm, 57mm and 78mm. The 78mm width webbing being used for the 83mm and 102mm flexators.

|   |       |       |       |       |
|---|-------|-------|-------|-------|
| Flexator Width (mm)                       | 42    | 60    | 83    | 102   |
| Webbing Width (mm)                        | 38    | 57    | 78    | 78    |
| Max Torque, T (Nm) @ 3.5 bar              | 4.55  | 7.87  | 12.30 | 15.63 |
| Output Shaft Radius, r (m)                | 0.014 | 0.014 | 0.014 | 0.014 |
| Force in Webbing Strap<br>$F = T / r$ (N) | 325   | 562   | 879   | 1116  |

Table E.2 - Webbing Strap Force Data.

From the graphs overleaf the following webbing data has been calculated:

Max. Tensile Stress,  $\sigma \approx 10$  (MN/m<sup>2</sup>)

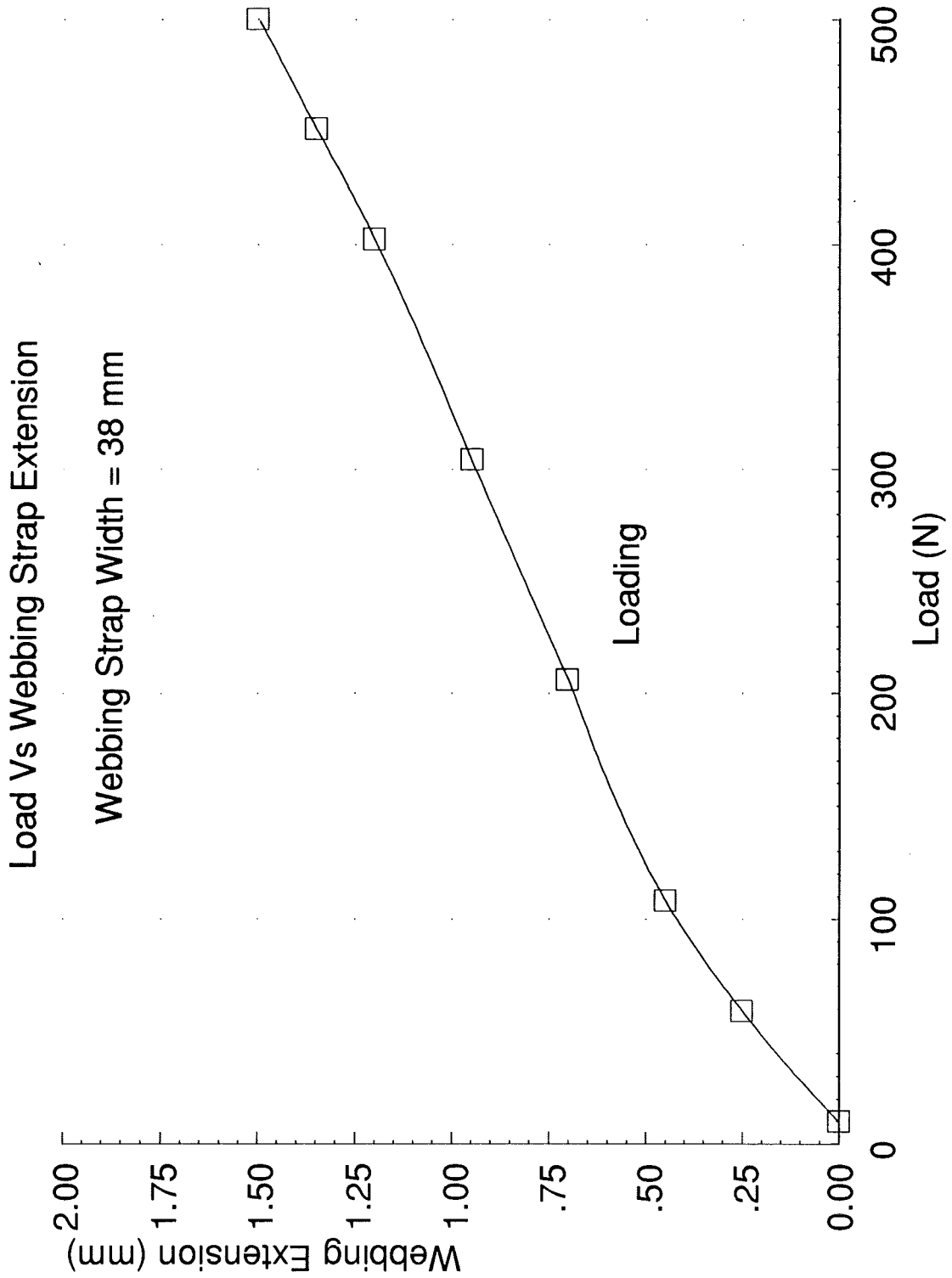
% Elongation <0.5

Young's Modulus,  $E \approx 2,100$  (MN/m<sup>2</sup>)

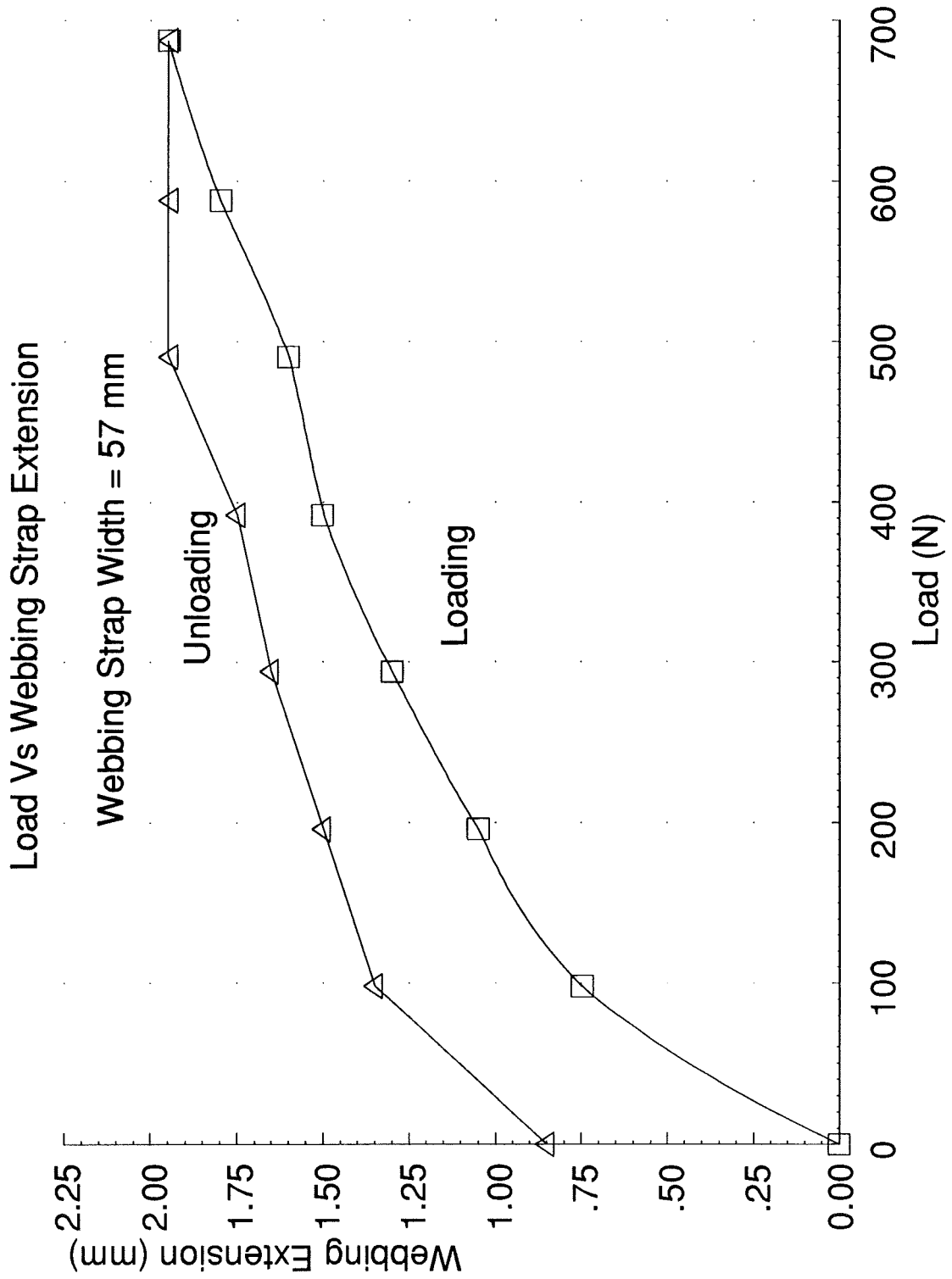
|                            |       |        |        |
|----------------------------|-------|--------|--------|
| Flat Width (mm)            | 38    | 57     | 78     |
| Thickness (mm)             | 1     | 1      | 1      |
| Min. Breaking Strength (N) | 6,675 | 10,000 | 13,350 |

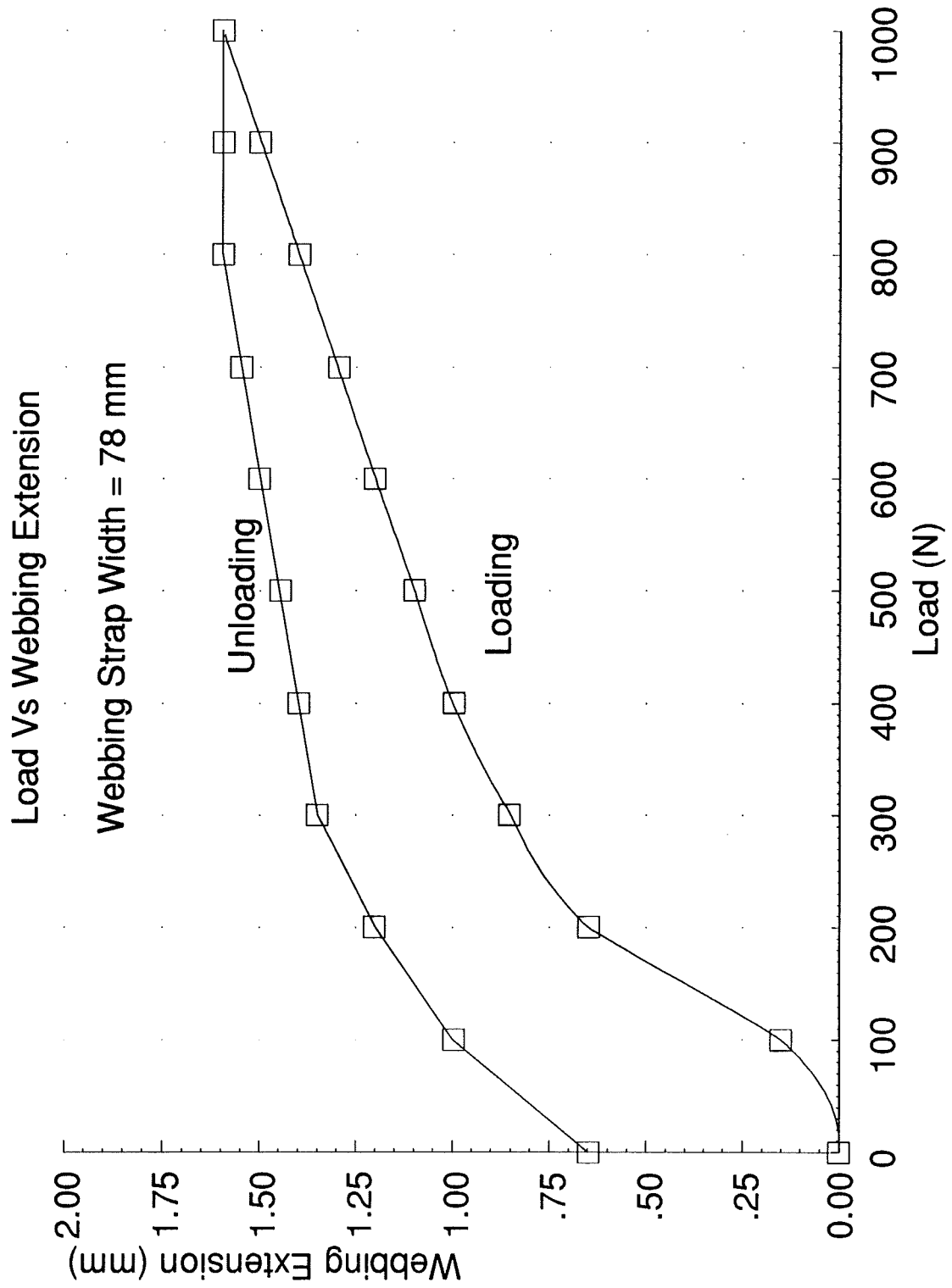
Table E.3 - Polyamide (Nylon 66) Webbing Properties


From the above table we can see that this type of webbing material can withstand far higher forces than those used in the current tests. However, it should be noted that at higher values of torque, careful consideration should be given to the level of increased force in the webbing strap, and hence the amount of elongation and residual deformation (creep).









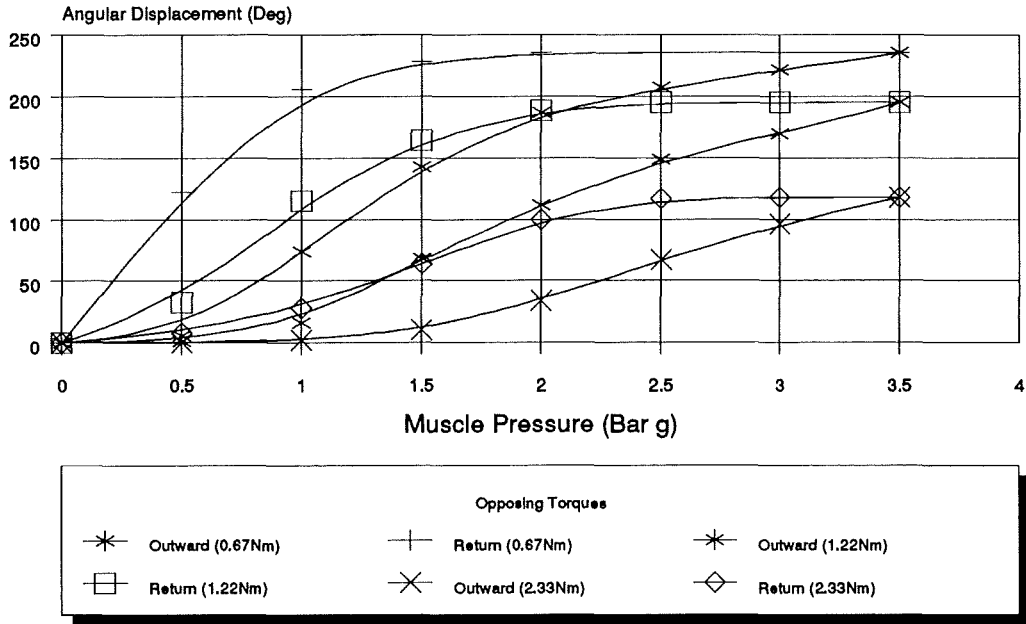


**APPENDIX F1 : FLEXATOR ACTUATOR STATIC TEST RESULTS**

---

### Static Muscle Tests

Muscle Type and Position: 42 x 90 ; 4

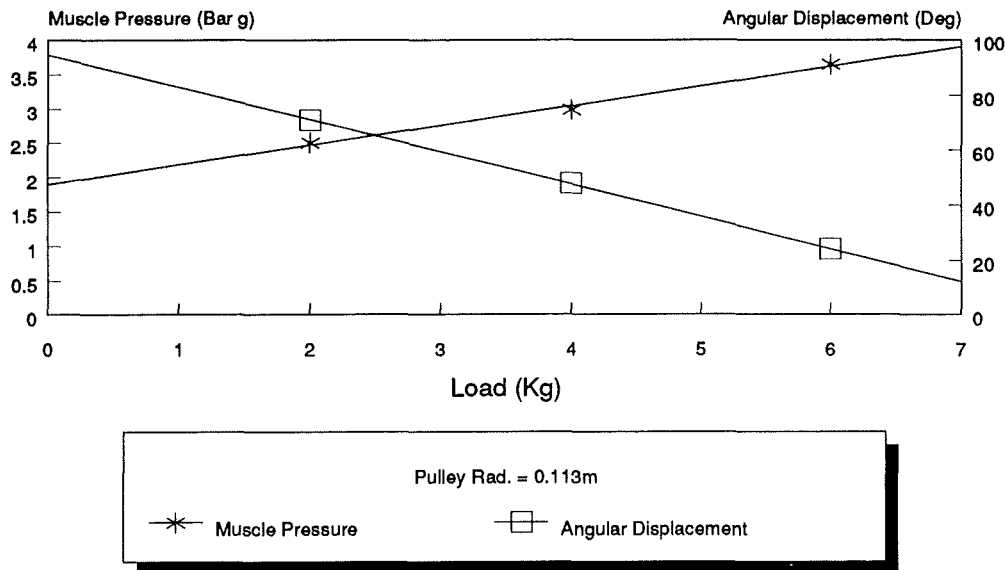


Date: 4/3/91

Figure F1.1

### Muscle Spring Stiffness

Muscle Type: 42 x 90 ; 4



4/3/91

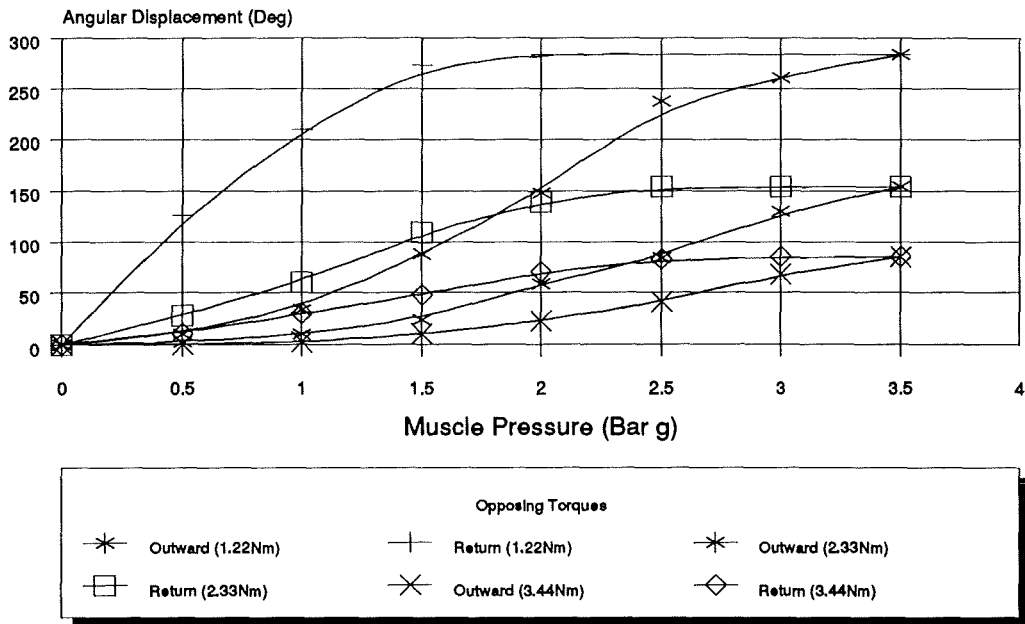
Set Point = 2.5 (Bar g) & 2 (Kg)

Spring Stiffness K = -0.0943 Nm/Deg

Figure F1.2

### Static Muscle Tests

Muscle Type and Position: 42 x 130 ; 3

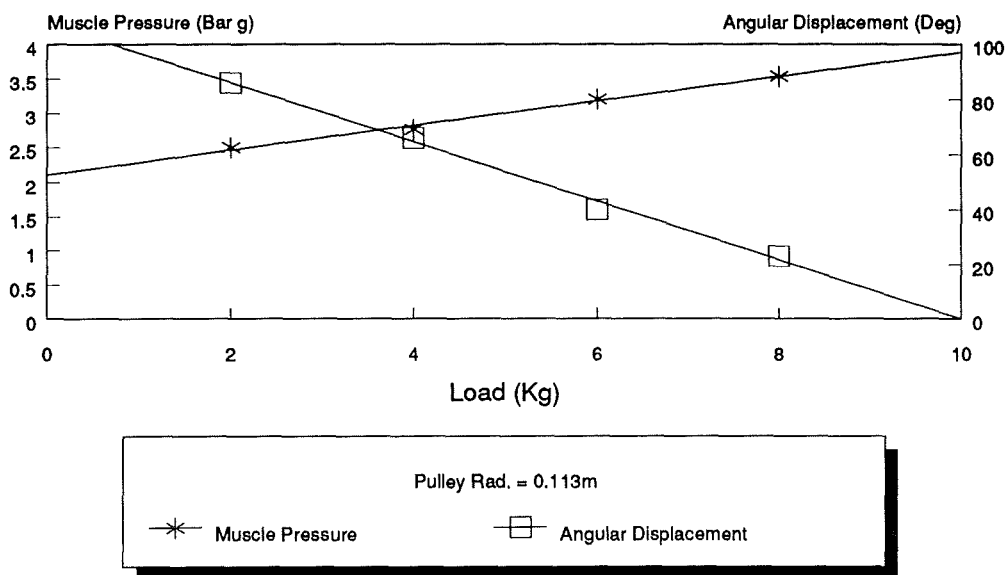


Date: 24/7/91

Figure F1.3

### Muscle Spring Stiffness

Muscle Type: 42 x 130 ; 3



24/7/91

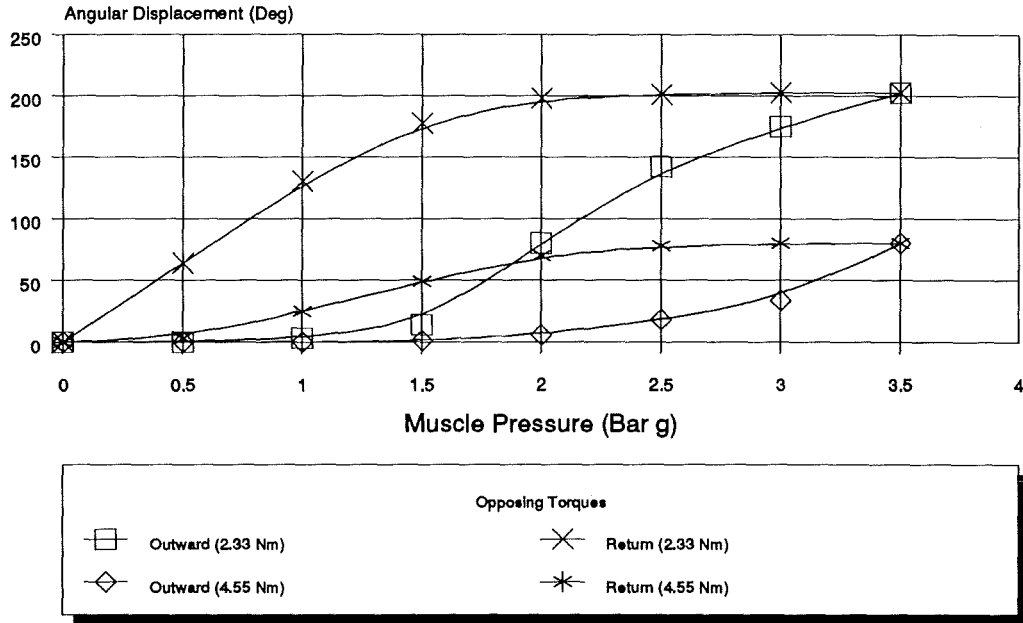
Set Point = 2.5 (Bar g) & 2 (Kg)

Spring Stiffness K = -0.1025 Nm/Deg

Figure F1.4

### Static Muscle Tests

Muscle Type and Position: 42 x 170 ; 1

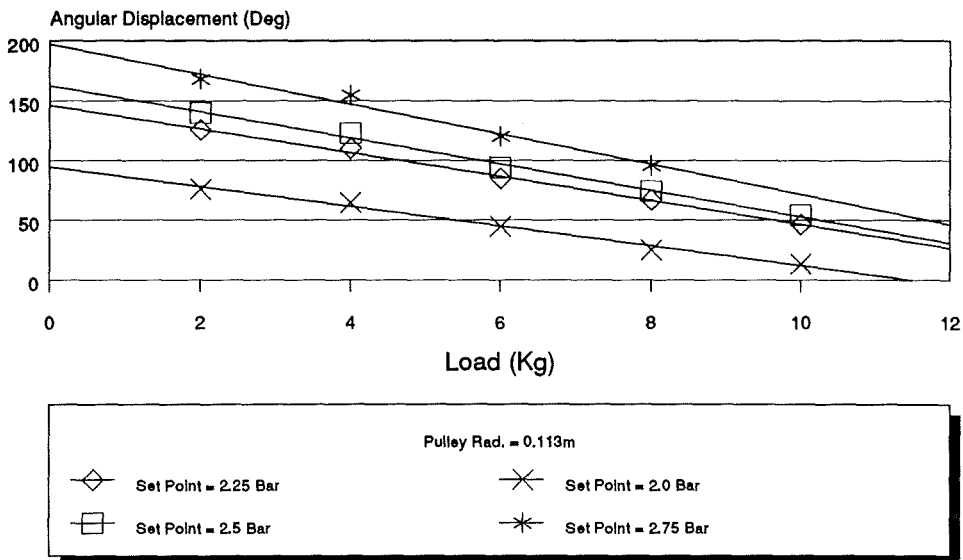


Date: 26/02/91

Figure F1.5

### Muscle Spring Stiffness

Muscle Type: 42x170 ; 1



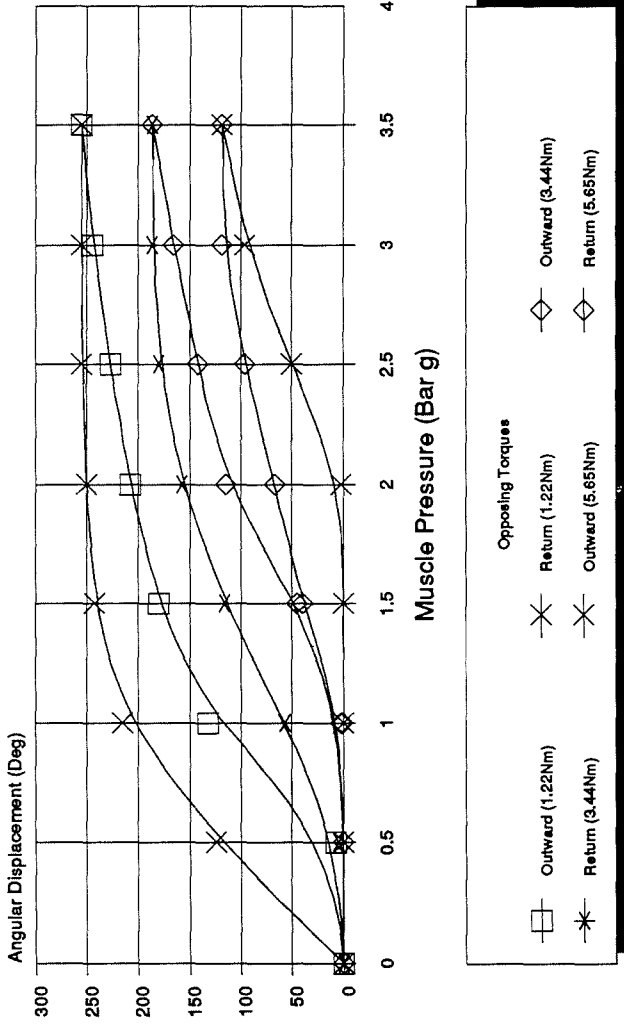
28/2/91

Spring Stiffness K = -0.1141 Nm/Deg (Av)

Figure F1.6

### Static Muscle Tests

Muscle Type and Position: 60 x 90 ; 5

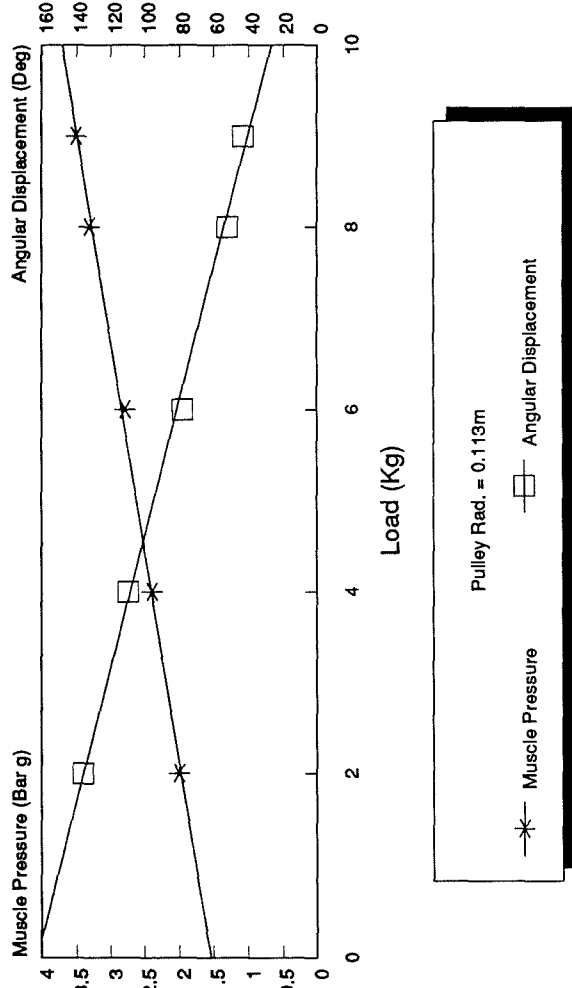


Date: 19/7/91

Figure F1.7

### Muscle Spring Stiffness

Muscle Type: 60 x 90 ; 4



4/3/91

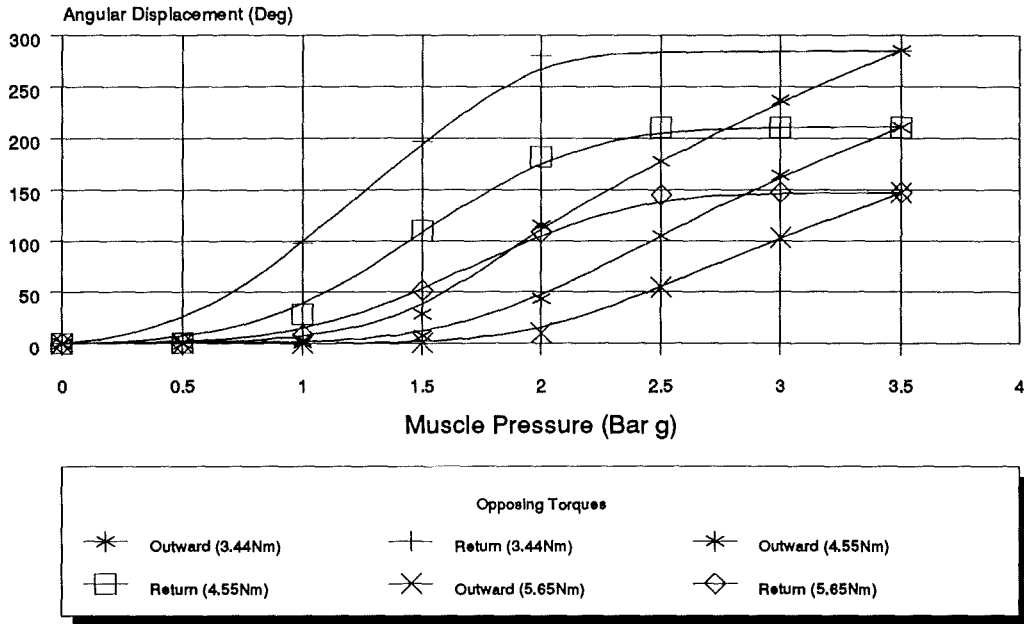
Set Point = 2 (Bar g) & 2 (Kg)

Spring Stiffness K = -0.0810 Nm/Deg

Figure F1.8

### Static Muscle Tests

Muscle Type and Position: 60 x 130 ; 3

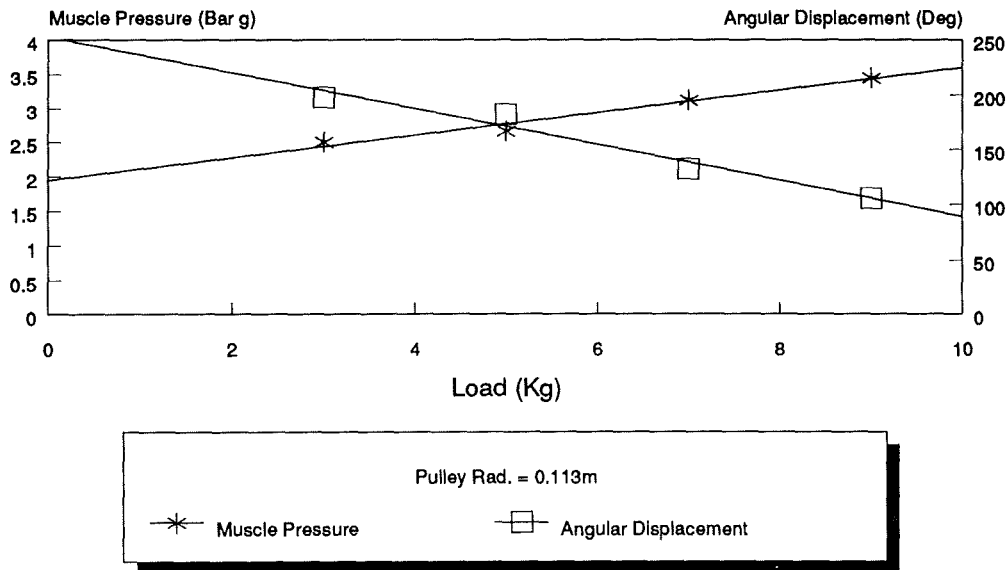


Date: 19/7/91

Figure F1.9

### Muscle Spring Stiffness

Muscle Type: 60 x 130 ; 3



4/3/91

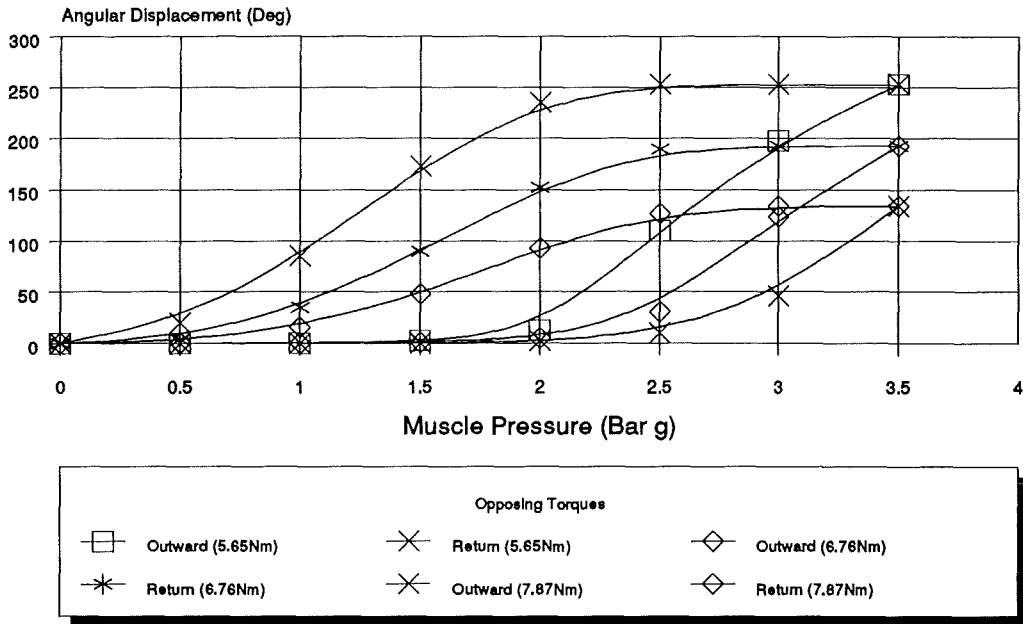
Set Point = 2.5 (Bar g) & 3 (Kg)  
Spring Stiffness K = -0.0707 Nm/Deg

Figure F1.10



### Static Muscle Tests

Muscle Type and Position: 60 x 170 ; 1

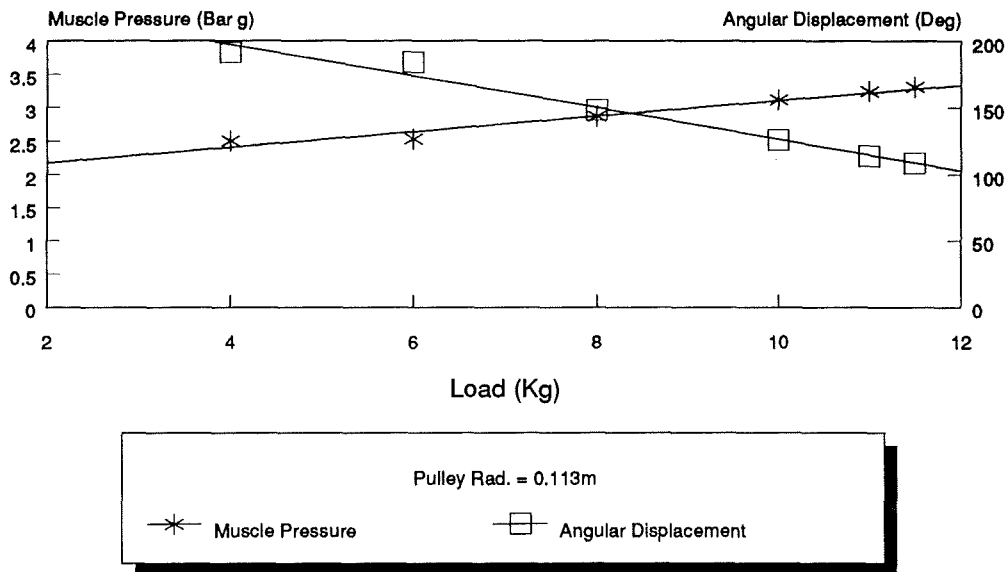


Date: 15/05/01

Figure F1.11

### Muscle Spring Stiffness

Muscle Type: 60 x 170 ; 1



10/4/01

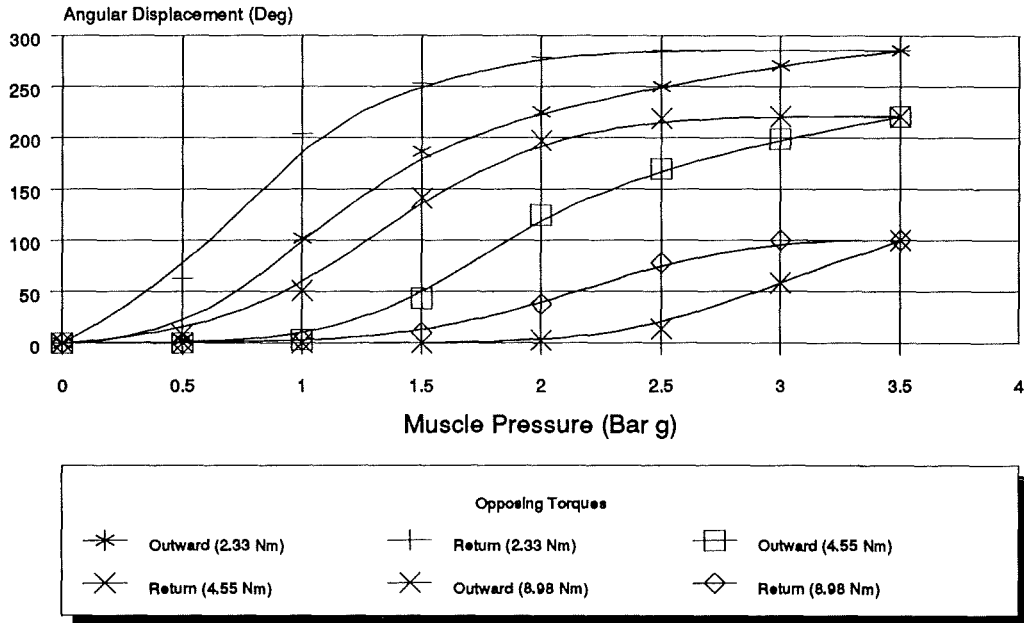
Set Point = 2.5 (Bar g) & 4 (Kg)

Spring Stiffness K = -0.1011 Nm/Deg

Figure F1.12

### Static Muscle Tests

Muscle Type and Position: 83 x 90 ; 4

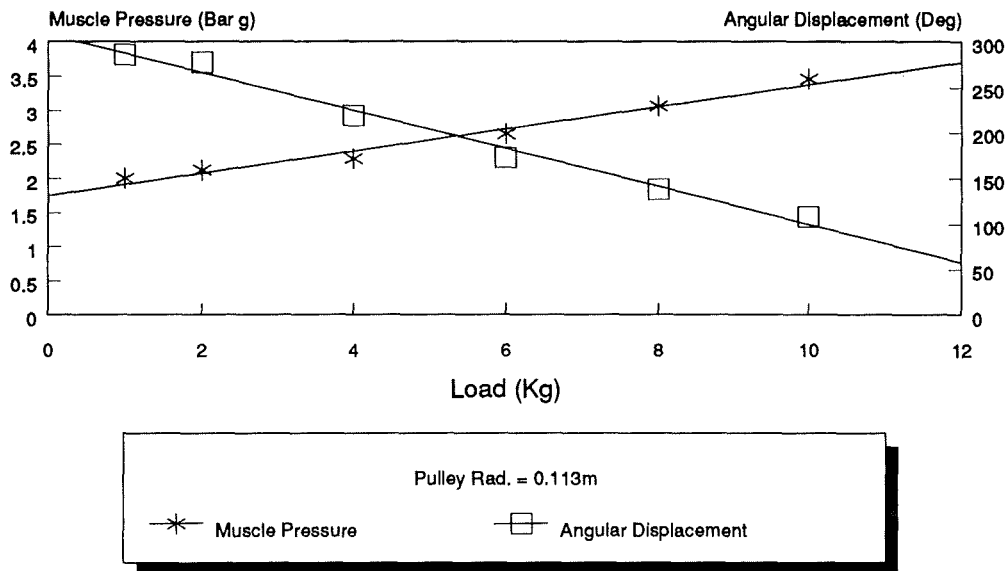


Date: 26/02/91

Figure F1.13

### Muscle Spring Stiffness

Muscle Type: 83x90 ; 4



26/2/91

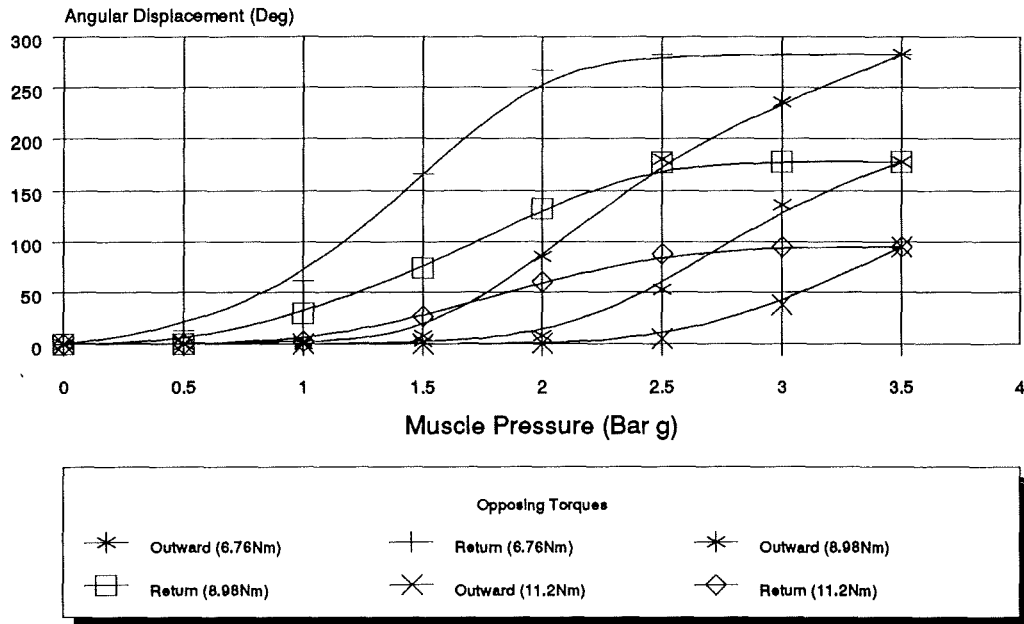
Set Point = 2 (Bar g) & 1 (Kg)

Spring Stiffness K = -0.0706 Nm/Deg

Figure F1.14

### Static Muscle Tests

Muscle Type and Position: 83 x 130 ; 3

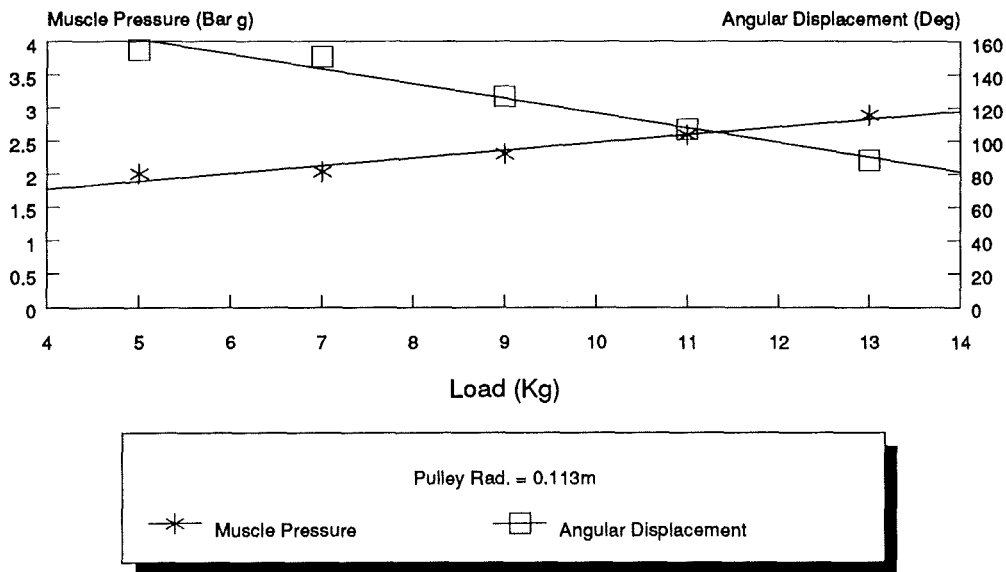


Date: 23/7/91

Figure F1.15

### Muscle Spring Stiffness

Muscle Type: 83 x 130 ; 3



23/7/91

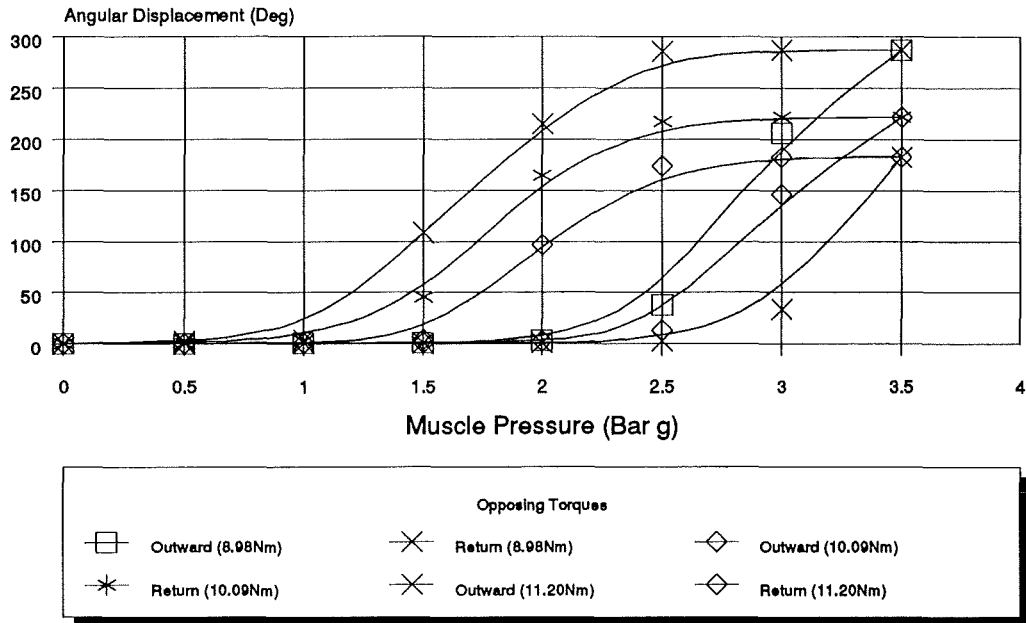
Set Point = 2.0 (Bar g) & 5 (Kg)

Spring Stiffness K = -0.1058 Nm/Deg

Figure F1.16

### Static Muscle Tests

Muscle Type and Position: 83 x 170 ; 1

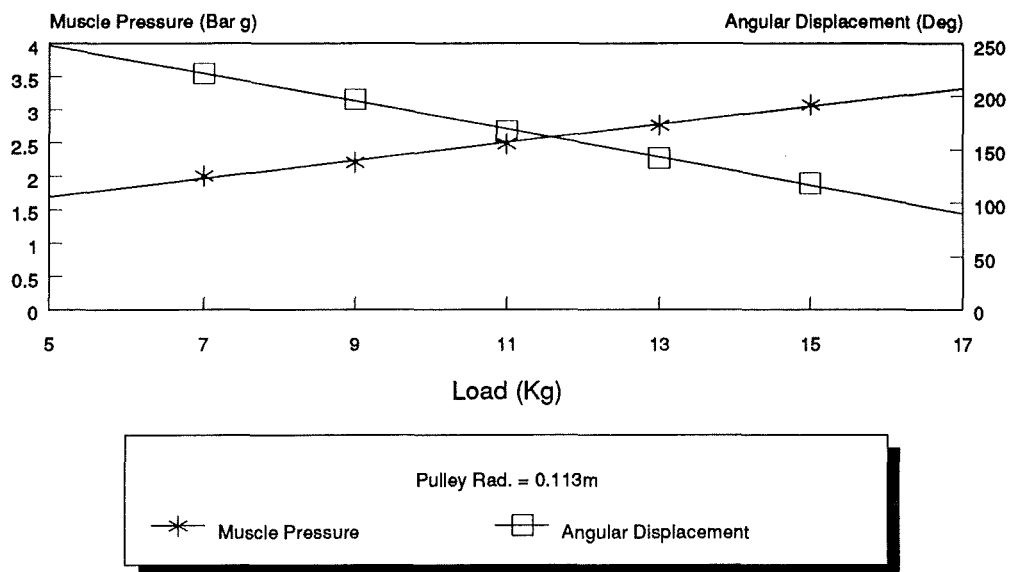


Date: 13/05/91

Figure F1.17

### Muscle Spring Stiffness

Muscle Type: 83 x 170 ; 1



13/5/91

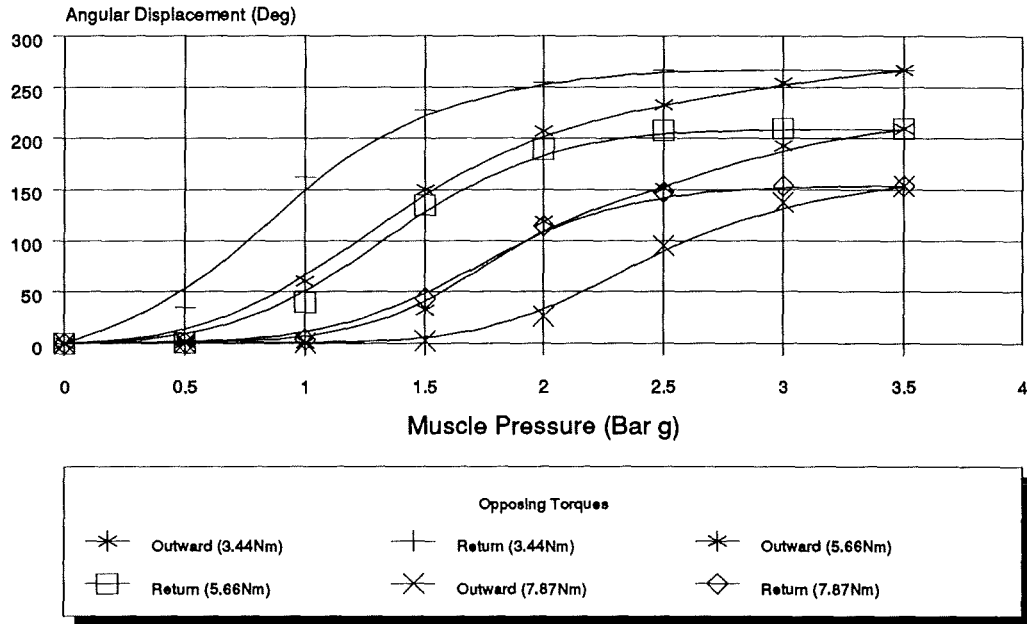
Set Point = 2 (Bar g) & 7 (Kg)

Spring Stiffness K = -0.0842 Nm/Deg

Figure F1.18

### Static Muscle Tests

Muscle Type and Position: 102 x 90 ; 4

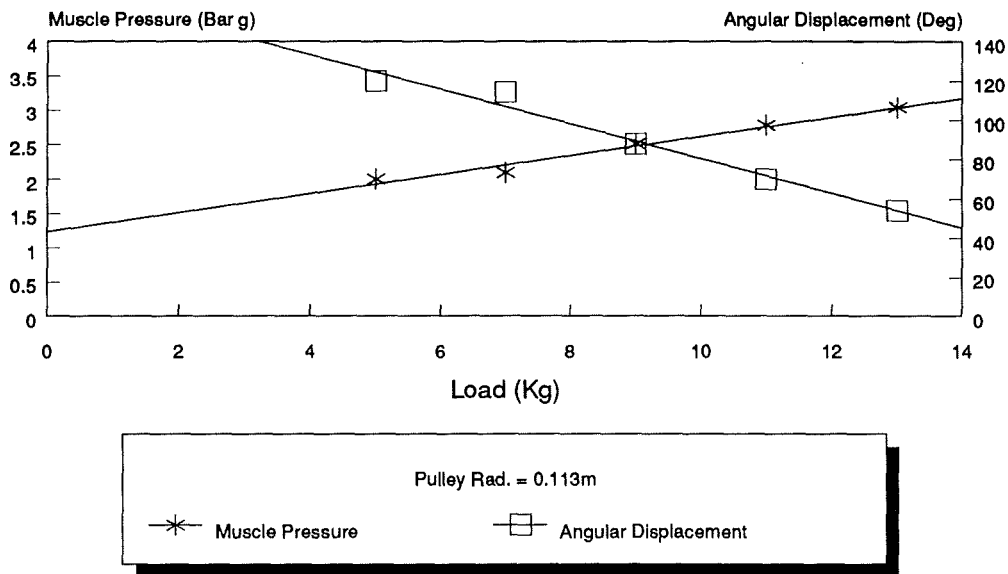


Date: 4/3/01

Figure F1.19

### Muscle Spring Stiffness

Muscle Type: 102 x 90 ; 4



4/3/01

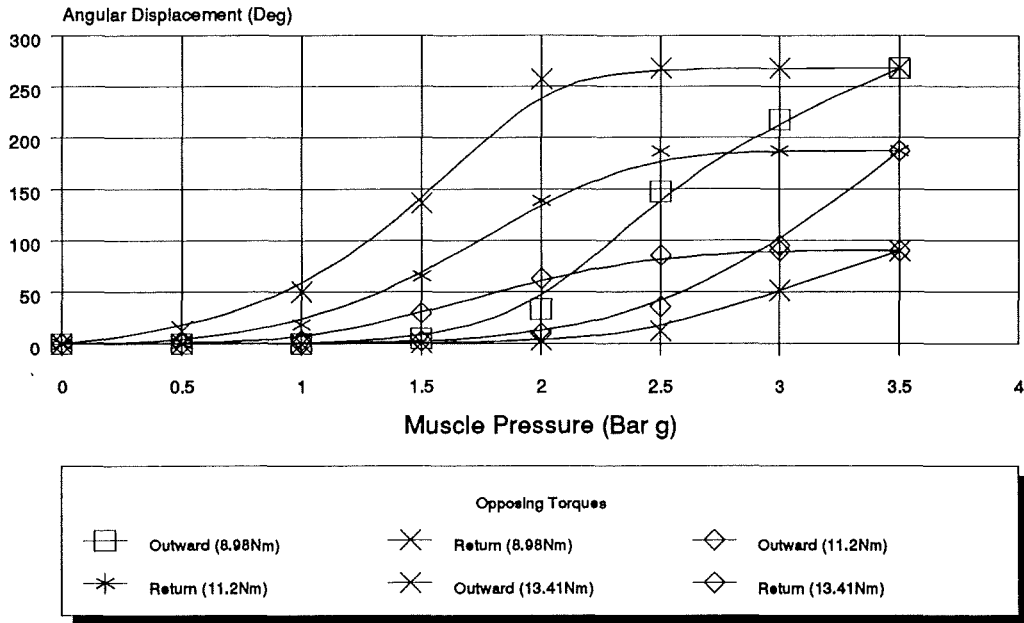
Set Point = 2 (Bar g) & 5 (Kg)

Spring Stiffness K = -0.1277 Nm/Deg

Figure F1.20

### Static Muscle Tests

Muscle Type and Position: 102 x 130 ; 3

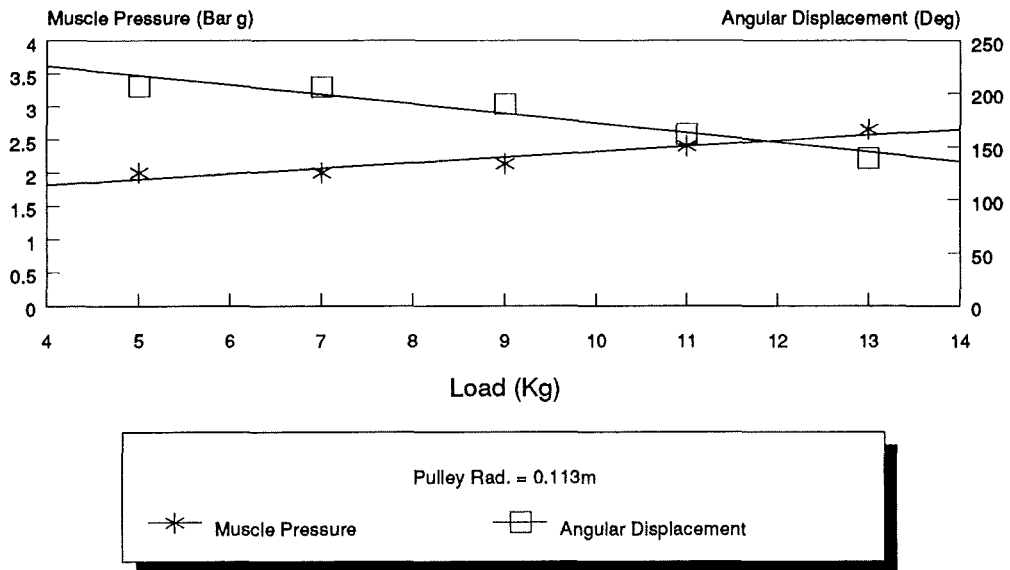


Date: 23/07/91

Figure F1.21

### Muscle Spring Stiffness

Muscle Type: 102 x 130 ; 3



23/7/91

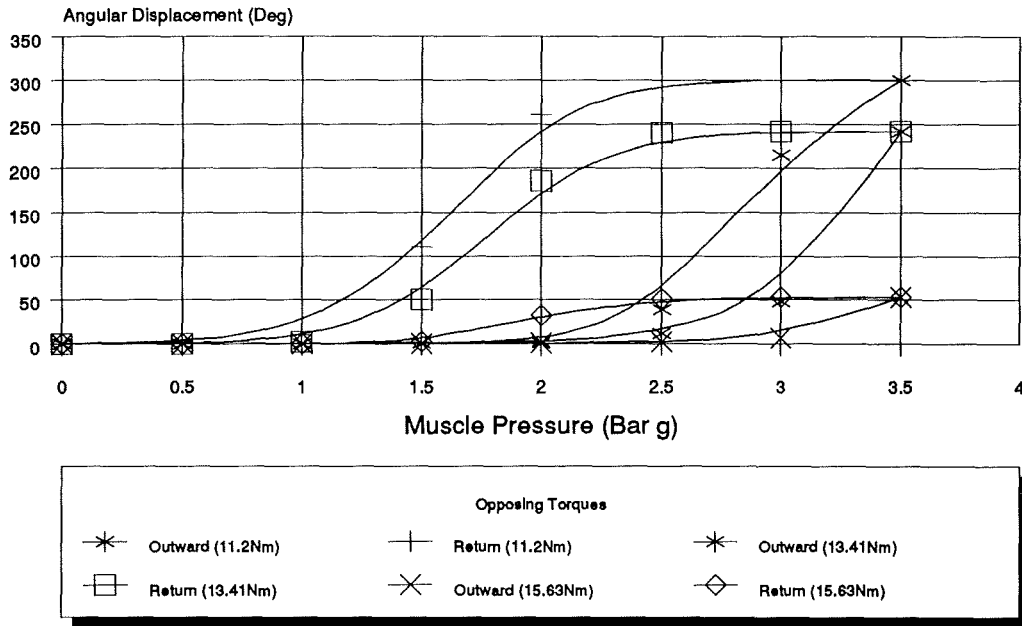
Set Point = 2.0 (Bar g) & 5 (Kg)

Spring Stiffness K = -0.0958 Nm/Deg

Figure F1.22

### Static Muscle Tests

Muscle Type and Position: 102 x 170 ; 1

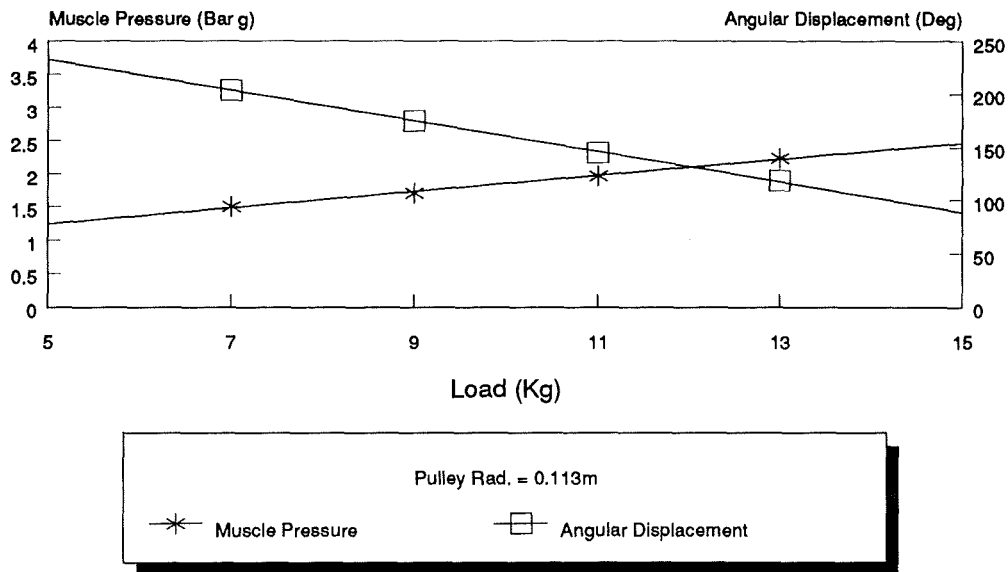


Date: 19/7/91

Figure F1.23

### Muscle Spring Stiffness

Muscle Type: 102 x 170 ; 1



21/5/91

Set Point = 1.5 (Bar g) & 7 (Kg)

Spring Stiffness K = -0.0769 Nm/Deg

Figure F1.24



**APPENDIX F2 : TABLE OF FLEXATOR HYSTERESIS VALUES**

---



Muscle types tested - 12 variations.  
Maximum hysteresis values as % of f.s.d.

Appendix F2 - Table of maximum hysteresis values.

| (A)<br>42 mm   | (B)<br>60 mm   | (C)<br>83 mm  | (D)<br>102 mm   | (E)<br>120 mm | Width<br>Length |
|--|--|---|---|---------------|-----------------|
| 0.67 Nm ~ 56.2 %<br>1.22 Nm ~ 50.8 %<br>2.33 Nm ~ 56.0 %   | 1.22 Nm ~ 45.9 %<br>2.33 Nm ~ 50.2 %<br>3.44 Nm ~ 38.2 %<br>4.55 Nm ~ 41.7 %<br>5.65 Nm ~ 55.1 % | 2.33 Nm ~ 33.1 %<br>4.55 Nm ~ 45.6 %<br>8.98 Nm ~ 60.8 %  | 3.44 Nm ~ 38.2 %<br>5.65 Nm ~ 49.3 %<br>7.87 Nm ~ 57.5 %<br>10.09 Nm ~ 67.0 %                         |               | 90 mm (1)       |
|  |  |   |   |               | 110 mm (2)      |
| 1.22 Nm ~ 65.1 %<br>1.77 Nm ~ 55.0 %<br>2.33 Nm ~ 55.2 %<br>2.88 Nm ~ 56.6 %<br>3.44 Nm ~ 56.5 % | 3.44 Nm ~ 58.9 %<br>4.55 Nm ~ 65.4 %<br>5.65 Nm ~ 66.7 %<br>6.76 Nm ~ 78.8 %                     | 6.76 Nm ~ 64.5 %<br>7.87 Nm ~ 75.0 %<br>8.98 Nm ~ 69.7 %<br>10.09 Nm ~ 85.9 %<br>11.20 Nm ~ 87.4 %  | 8.98 Nm ~ 83.2 %<br>10.09 Nm ~ 71.6 %<br>11.20 Nm ~ 80.2 %<br>12.30 Nm ~ 84.6 %<br>13.41 Nm ~ 81.1 %  |               | 130 mm (3)      |
|  |  |   |   |               | 150 mm (4)      |
| 2.33 Nm ~ 80.8 %<br>4.55 Nm ~ 80.0 %   | 5.65 Nm ~ 88.1 %<br>6.76 Nm ~ 82.4 %<br>7.87 Nm ~ 87.3 %   | 7.87 Nm ~ 83.5 %<br>8.98 Nm ~ 86.4 %<br>10.09 Nm ~ 92.3 %<br>11.20 Nm ~ 94.0 %<br>12.30 Nm ~ 95.7 % | 11.20 Nm ~ 87.3 %<br>12.30 Nm ~ 93.7 %<br>13.41 Nm ~ 94.6 %<br>14.52 Nm ~ 97.7 %<br>15.63 Nm ~ 92.5 % |               | 170 mm (5)      |



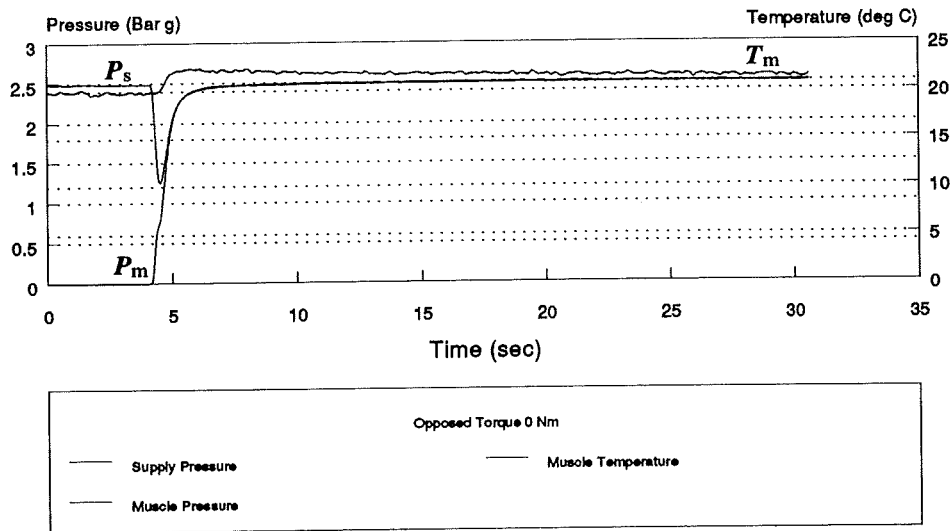
**APPENDIX G : FLEXATOR AIR TEMPERATURE ANALYSIS**



Muscle Type: 42x170, Step Input 2.5 Bar

"Pts/Chan "250

"Samples/s "31



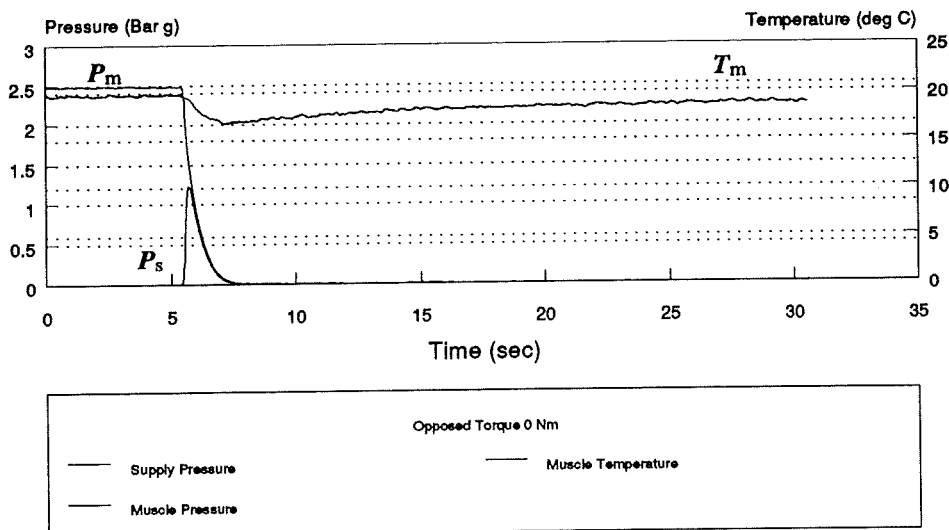
18/2/01

Figure G.1

Muscle Type: 42x170, Exhaust to atm.

"Pts/Chan "250

"Samples/s "31



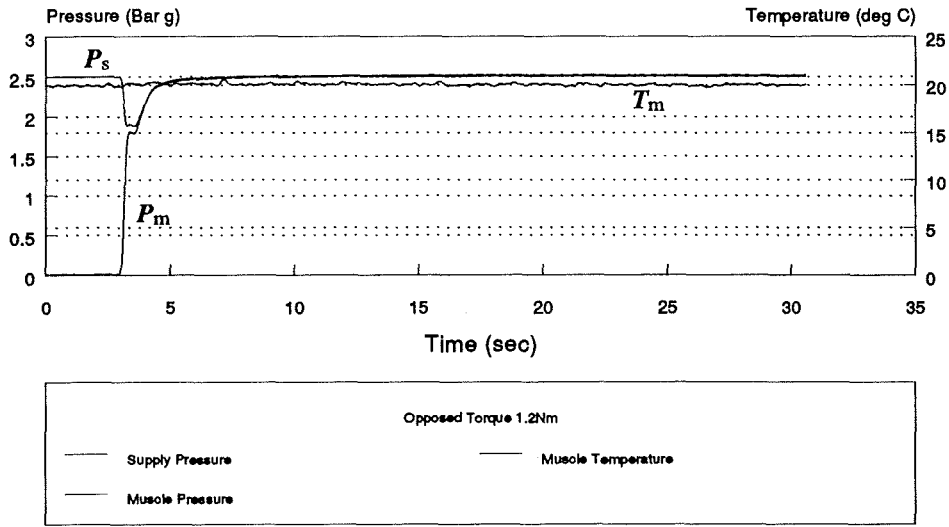
18/2/01

Figure G.2

Muscle Type: 42x170, Step Input 2.5 Bar

"Pts/Chan "250

"Samples/s "31



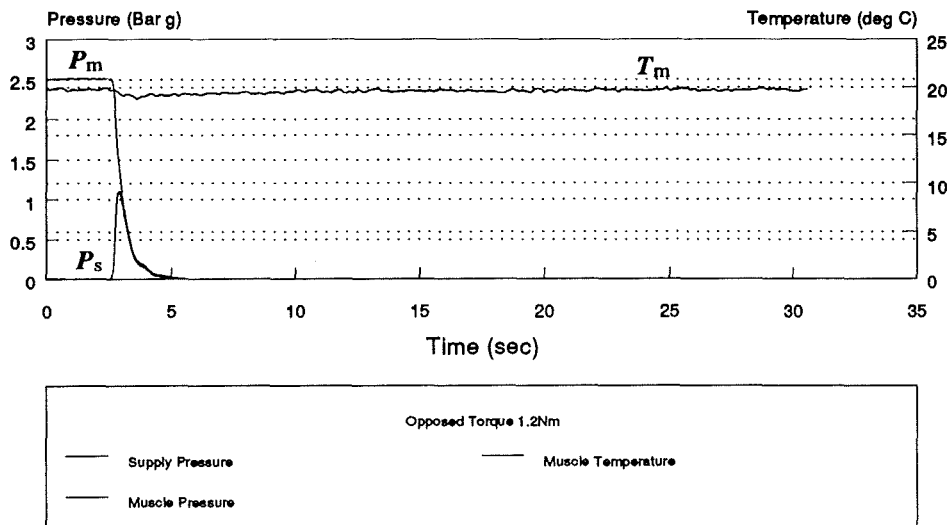
18/2/91

Figure G.3

Muscle Type: 42x170, Exhaust to atm.

"Pts/Chan "250

"Samples/s "31



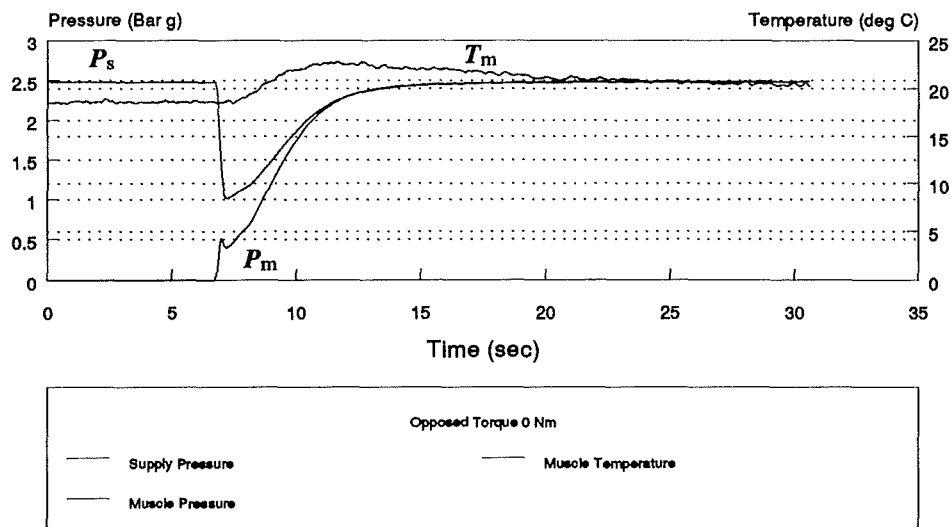
18/2/91

Figure G.4

Muscle Type: 120x170, Step Input 2.5 Bar

"Pts/Chan "250

"Samples/s "31



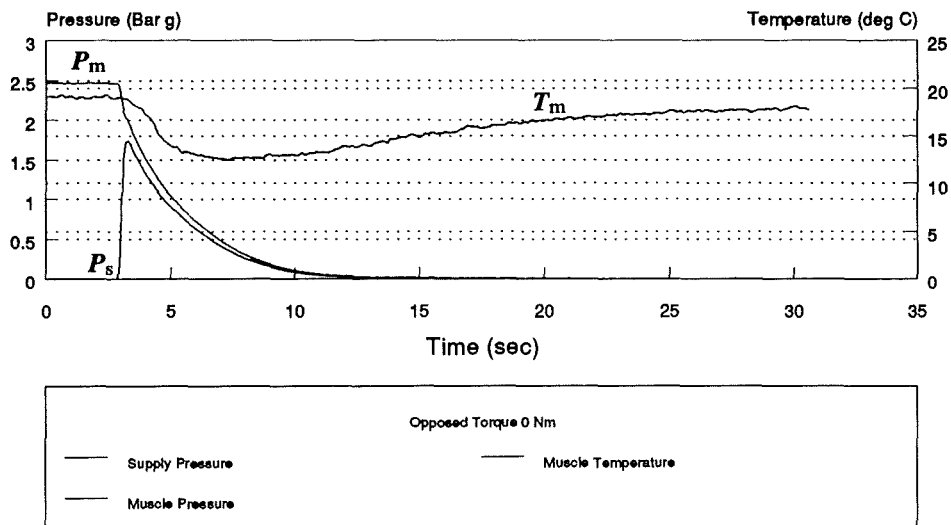
13/2/91

Figure G.5

Muscle Type: 120x170, Exhaust to atm.

"Pts/Chan "250

"Samples/s "31



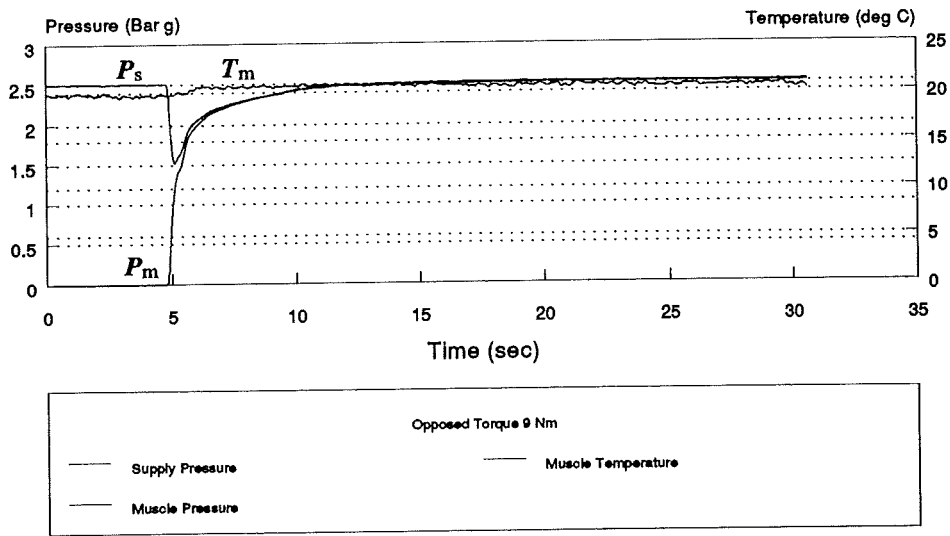
13/2/91

Figure G.6

Muscle Type: 120x170, Step Input 2.5 Bar

"Pts/Chan "250

"Samples/s "31



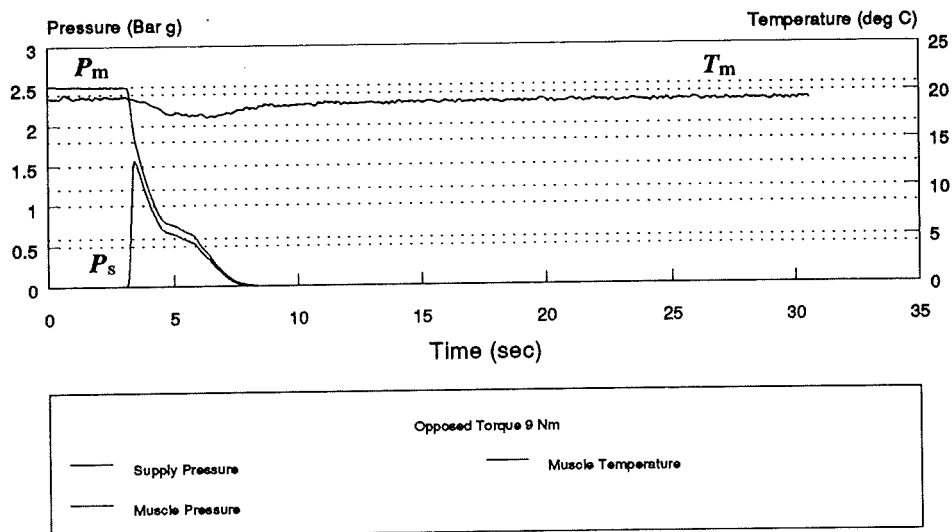
13/2/91

Figure G.7

Muscle Type: 120x170, Exhaust to atm.

"Pts/Chan "250

"Samples/s "31



13/2/91

Figure G.8

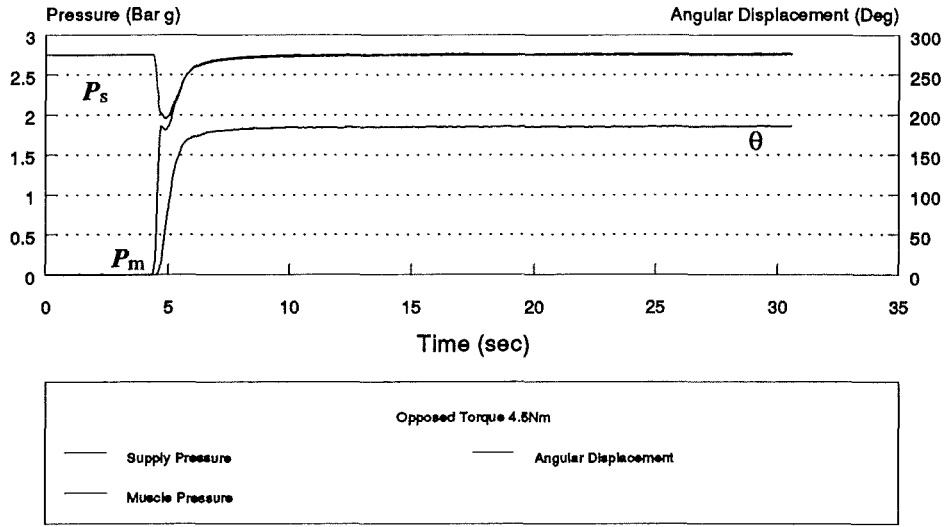


**APPENDIX H : TIME DELAY & SUPPLY LINE PRESSURE DROP**

Muscle Type: 83x90, Step Input 2.75 Bar

"Pts/Chan "250

"Samples/s "31



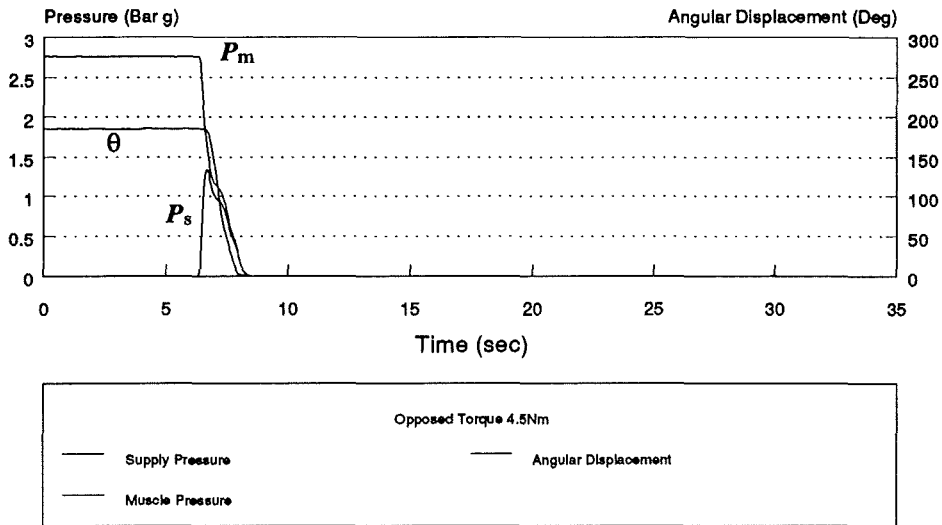
22/2/91

Figure H.1

Muscle Type: 83x90, Exhaust to atm.

"Pts/Chan "250

"Samples/s "31



22/2/91

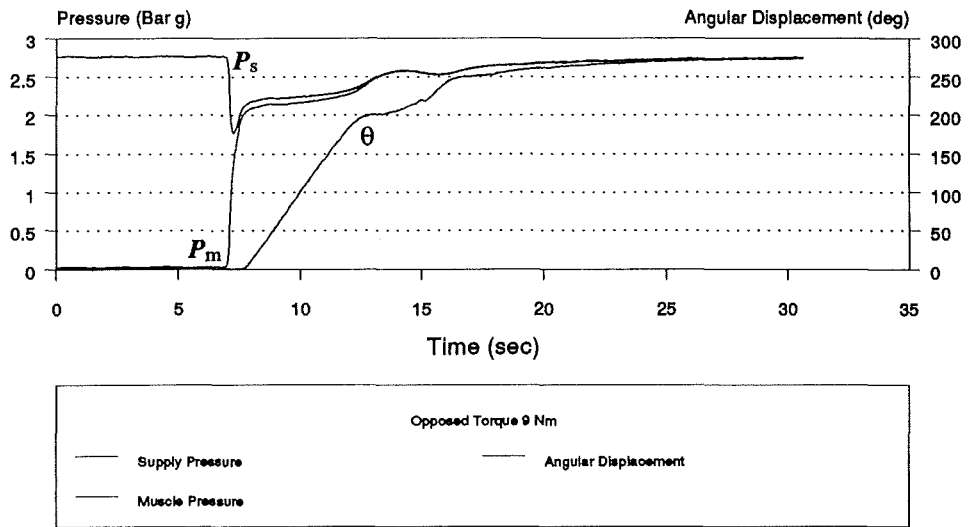
Figure H.2



Muscle Type:102x150, Step Input 2.75 Bar

"Pts/Chan "250

"Samples/s "31



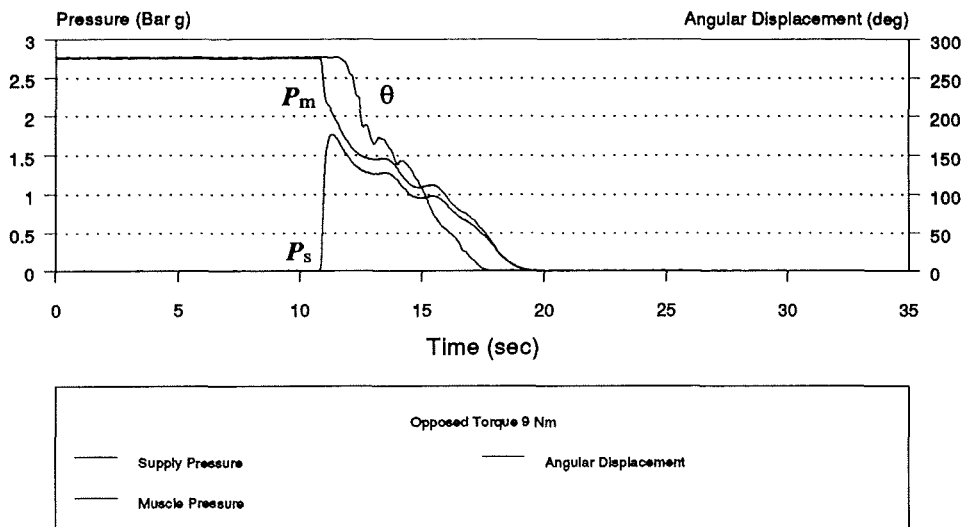
31/8/90

Figure H.3

Muscle Type:102x150 Exhaust to atm.

"Pts/Chan "250

"Samples/s "31



31/8/90

Figure H.4



**APPENDIX J : STIFFNESS DATA FOR THE DUAL FLEXATOR ACTUATOR**

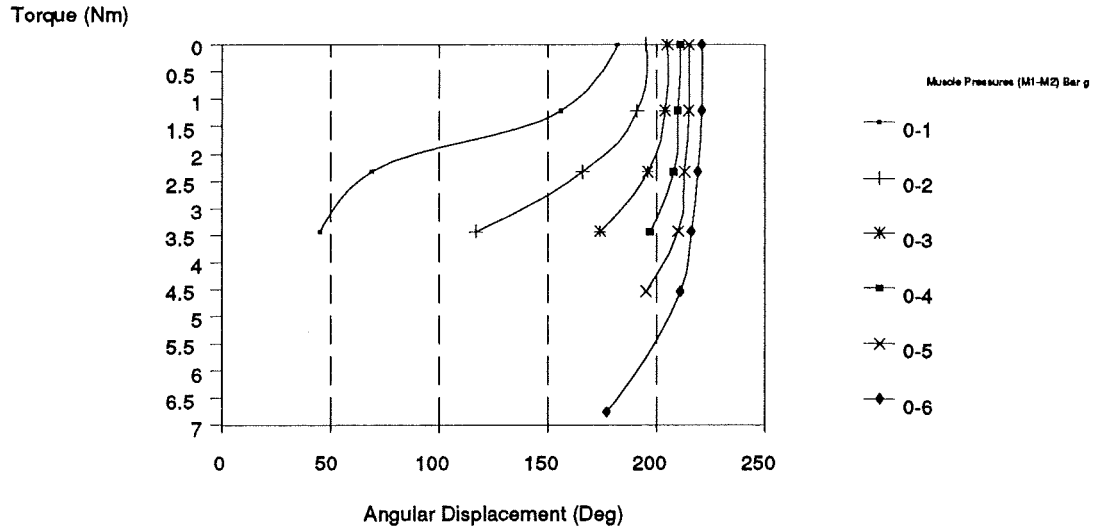
| Flexator 1       | Flexator 2       | Load Torque (Nm) |        |        |        |        |
|------------------|------------------|------------------|--------|--------|--------|--------|
|                  |                  | 1.219            | 2.328  | 3.436  | 4.545  | 6.762  |
| Pressure (bar g) | Pressure (bar g) |                  |        |        |        |        |
| 0                | 0                | /                | /      | /      | /      | /      |
| 0                | 1                | 0.0469           | 0.0206 | 0.0251 | /      | /      |
| 0                | 2                | 0.3048           | 0.0803 | 0.0440 | /      | /      |
| 0                | 3                | 1.2194           | 0.2586 | 0.1108 | /      | /      |
| 0                | 4                | 1.2194           | 0.7759 | 0.2454 | /      | /      |
| 0                | 5                | $\infty$         | 1.1639 | 0.6873 | 0.2272 | /      |
| 0                | 6                | $\infty$         | 1.1639 | 0.6873 | 0.4545 | 0.1537 |
| 1                | 0                | 0.0813           | 0.1058 | 0.1273 | 0.1420 | 0.1734 |
| 1                | 1                | 0.0348           | 0.0408 | 0.0446 | 0.0473 | 0.0615 |
| 1                | 2                | 0.0938           | 0.0495 | 0.0446 | /      | /      |
| 1                | 3                | 0.6095           | 0.1225 | 0.0687 | /      | /      |
| 1                | 4                | 1.2194           | 0.3879 | 0.1273 | /      | /      |
| 1                | 5                | $\infty$         | 0.7759 | 0.3124 | 0.1567 | /      |
| 1                | 6                | $\infty$         | /      | 0.4909 | 0.2673 | 0.1252 |
| 2                | 0                | 0.2032           | 0.2116 | 0.2291 | 0.2525 | 0.2705 |
| 2                | 1                | 0.0610           | 0.0529 | 0.0573 | 0.0689 | 0.0914 |
| 2                | 2                | 0.0554           | 0.0517 | 0.0545 | 0.0598 | 0.0663 |
| 2                | 3                | 0.1742           | 0.0931 | 0.0818 | /      | /      |

| Flexator 1       | Flexator 2       | Load Torque (Nm) |        |        |        |        |
|------------------|------------------|------------------|--------|--------|--------|--------|
|                  |                  | 1.219            | 2.328  | 3.436  | 4.545  | 6.762  |
| Pressure (bar g) | Pressure (bar g) |                  |        |        |        |        |
| 2                | 4                | 1.2194           | 0.2116 | 0.1145 | /      | /      |
| 2                | 5                | 1.2194           | 0.2910 | 0.1494 | 0.0988 | 0.0835 |
| 2                | 6                | 1.2194           | 0.7759 | 0.4295 | 0.2272 | 0.1276 |
| 3                | 0                | 0.2439           | 0.2328 | 0.2643 | 0.2674 | 0.3074 |
| 3                | 1                | 0.0717           | 0.0647 | 0.0799 | 0.0947 | 0.1229 |
| 3                | 2                | 0.0762           | 0.0727 | 0.0799 | 0.0842 | 0.0825 |
| 3                | 3                | 0.1219           | 0.0931 | 0.0818 | 0.0812 | 0.0889 |
| 3                | 4                | 0.2439           | 0.1369 | 0.1273 | 0.1165 | /      |
| 3                | 5                | 1.2194           | 0.2586 | 0.1494 | 0.1298 | /      |
| 3                | 6                | $\infty$         | 0.5819 | 0.2643 | 0.1623 | 0.1352 |
| 4                | 0                | 0.3048           | 0.2910 | 0.2864 | 0.2841 | 0.3074 |
| 4                | 1                | 0.0762           | 0.1058 | 0.1227 | 0.1420 | 0.1734 |
| 4                | 2                | 0.0938           | 0.1012 | 0.1041 | 0.1010 | 0.1009 |
| 4                | 3                | 0.0938           | 0.0895 | 0.0881 | 0.0947 | 0.1024 |
| 4                | 4                | 0.1355           | 0.1225 | 0.1145 | 0.1082 | 0.1056 |
| 4                | 5                | 0.3048           | 0.1552 | 0.1432 | 0.1377 | 0.1276 |
| 4                | 6                | 1.2194           | 0.3325 | 0.2021 | 0.1748 | 0.1610 |
| 5                | 0                | 0.2439           | 0.2587 | 0.2864 | 0.3030 | 0.3220 |

| Flexator 1       | Flexator 2       | Load Torque (Nm) |        |        |        |        |
|------------------|------------------|------------------|--------|--------|--------|--------|
| Pressure (bar g) | Pressure (bar g) | 1.219            | 2.328  | 3.436  | 4.545  | 6.762  |
| 5                | 1                | 0.1742           | 0.1791 | 0.2021 | 0.2272 | 0.2504 |
| 5                | 2                | 0.1219           | 0.1164 | 0.1074 | 0.0967 | 0.1146 |
| 5                | 3                | 0.0871           | 0.0931 | 0.1011 | 0.1057 | 0.1127 |
| 5                | 4                | 0.1524           | 0.1164 | 0.1041 | 0.1057 | 0.1108 |
| 5                | 5                | 0.2032           | 0.1663 | 0.1562 | 0.1337 | 0.1208 |
| 5                | 6                | 0.6097           | 0.2587 | 0.2148 | 0.1894 | 0.1691 |
| 6                | 0                | 0.4065           | 0.3326 | 0.3818 | 0.3496 | 0.3757 |
| 6                | 1                | 0.2032           | 0.2328 | 0.2643 | 0.2674 | 0.3074 |
| 6                | 2                | 0.1524           | 0.1293 | 0.1185 | 0.1082 | 0.1252 |
| 6                | 3                | 0.1016           | 0.1108 | 0.1185 | 0.1196 | 0.1300 |
| 6                | 4                | 0.1108           | 0.0931 | 0.0955 | 0.1010 | 0.1091 |
| 6                | 5                | 0.1524           | 0.1455 | 0.1145 | 0.1082 | 0.1091 |
| 6                | 6                | 0.2439           | 0.2116 | 0.1909 | 0.1818 | 0.1409 |

# Dual Flexator Stiffness Graph

Muscle Type: 60 x 90 ; 5

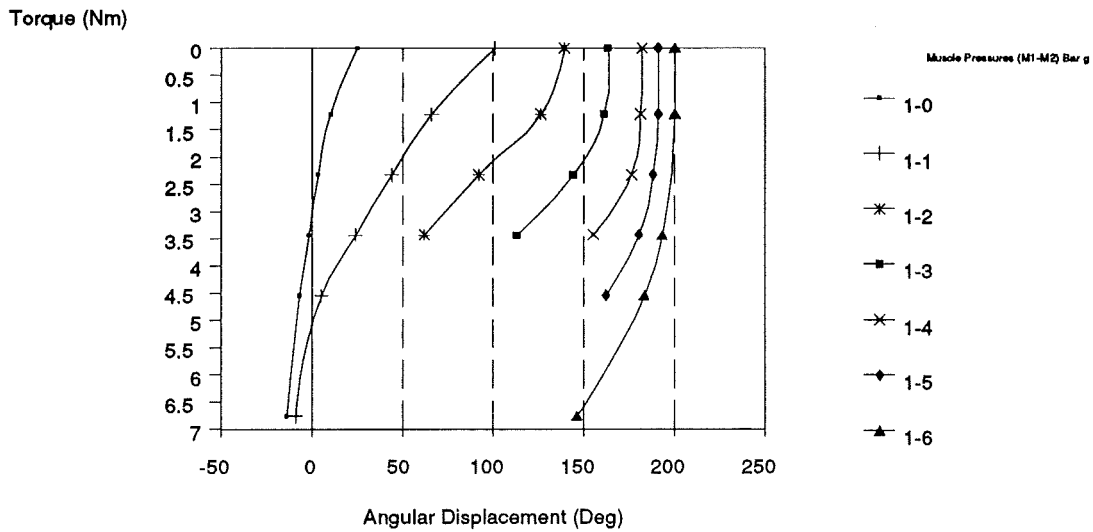


April 1992

Figure J.1

# Dual Flexator Stiffness Graph

Muscle Type: 60 x 90 ; 5

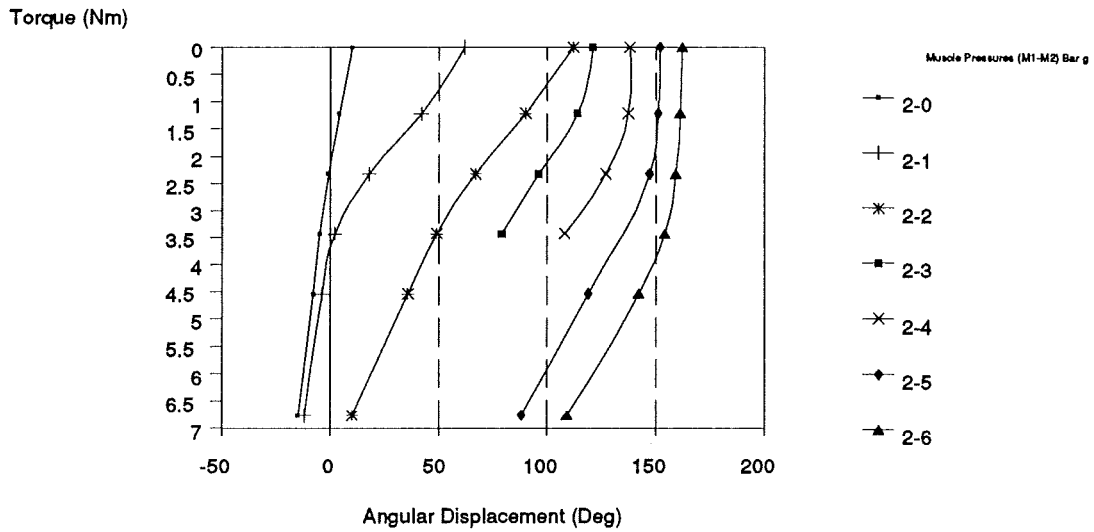


April 1992

Figure J.2

# Dual Flexator Stiffness Graph

Muscle Type: 60 x 90 ; 5

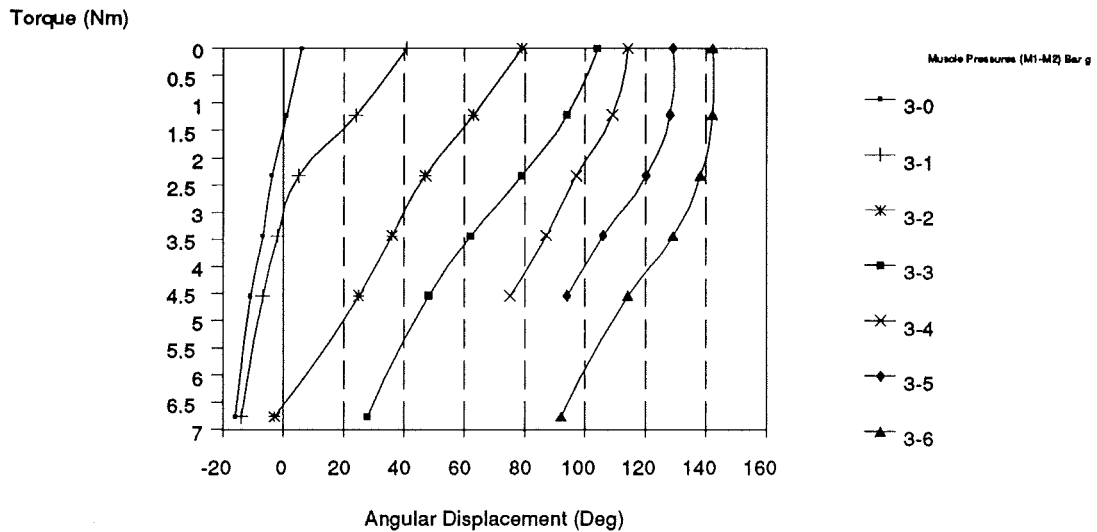


April 1992

Figure J.3

# Dual Flexator Stiffness Graph

Muscle Type: 60 x 90 ; 5

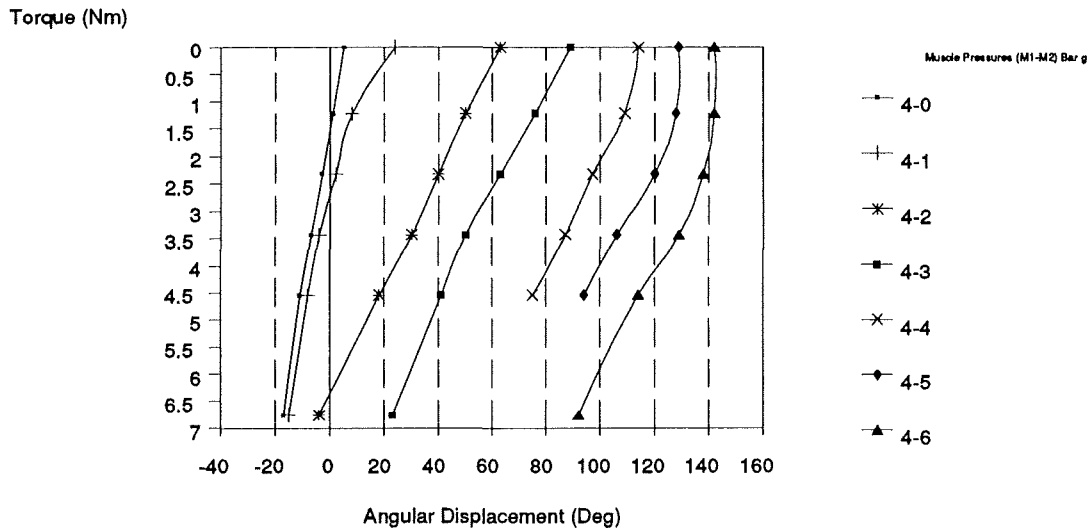


April 1992

Figure J.4

# Dual Flexator Stiffness Graph

Muscle Type: 60 x 90 ; 5

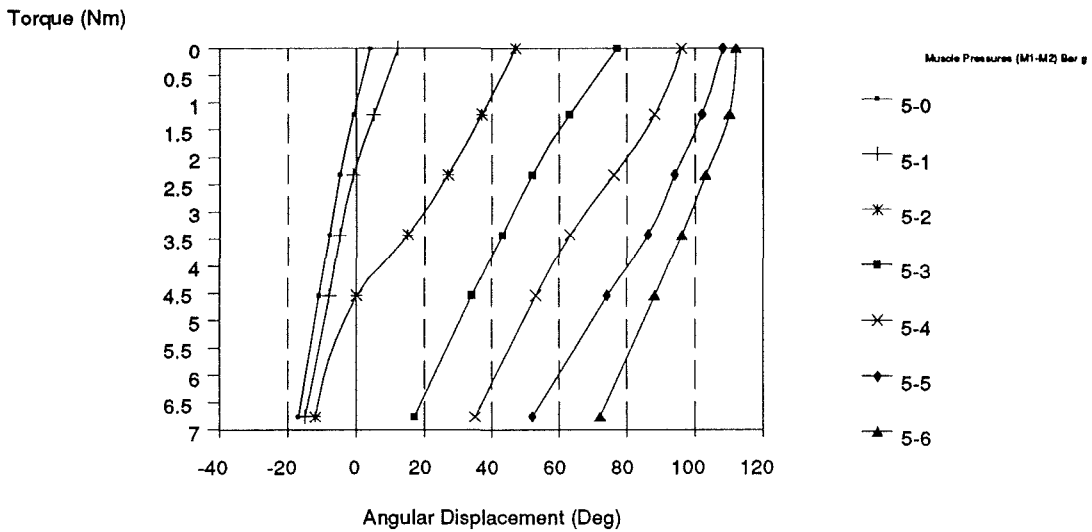


April 1992

Figure J.5

# Dual Flexator Stiffness Graph

Muscle Type: 60 x 90 ; 5



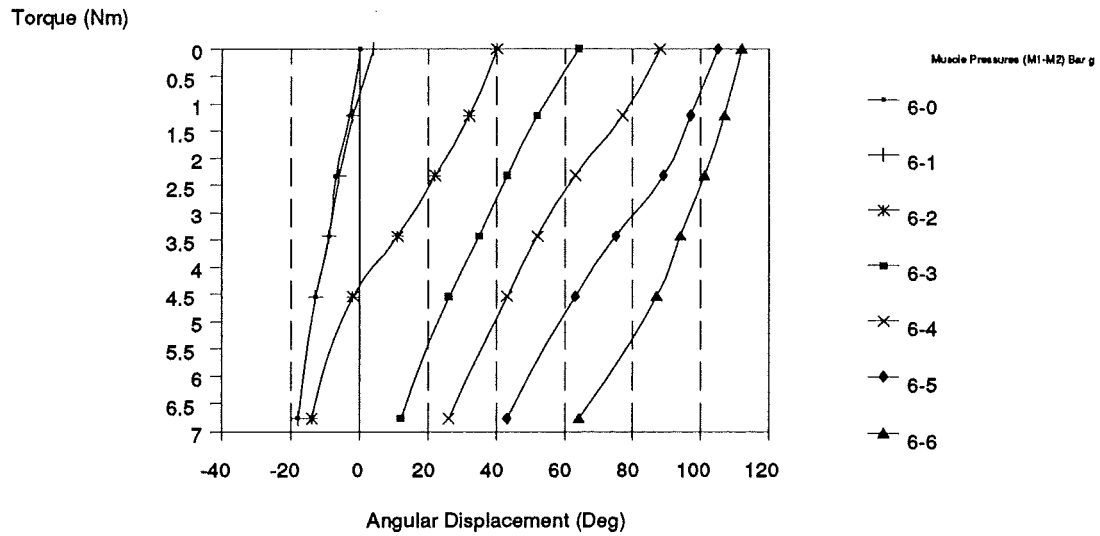
April 1992

Figure J.6



# Dual Flexator Stiffness Graph

Muscle Type: 60 x 90 ; 5

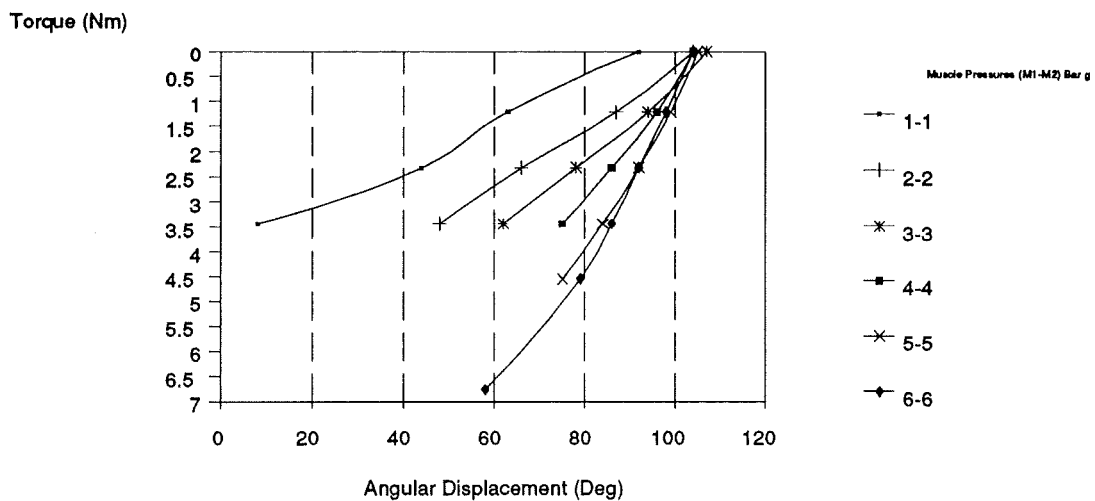


April 1992

Figure J.7

# Dual Flexator Stiffness Graph

Muscle Type: 60 x 90 ; 5



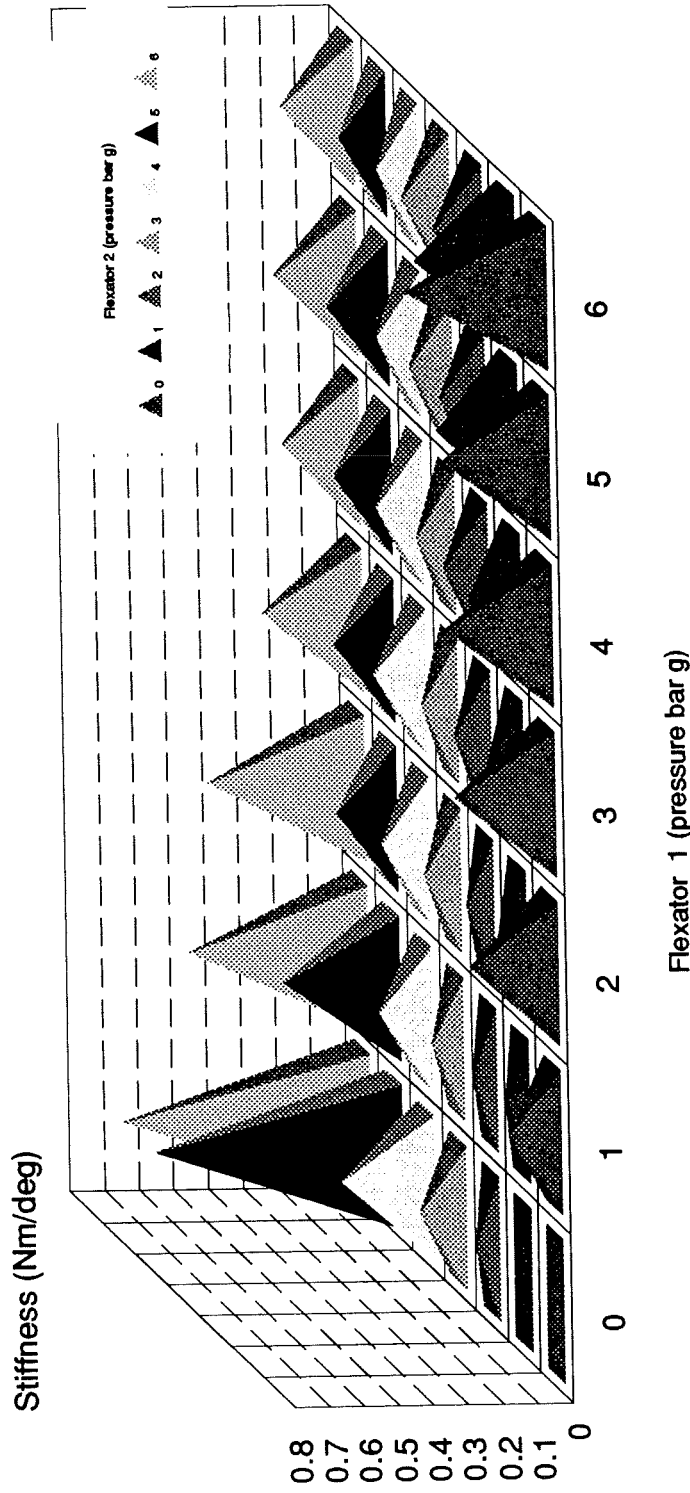
April 1992

Stiffness ranges from 0.0446 to 0.1909 Nm/Deg

Figure J.8

# Dual Flexator Stiffness Graph

Muscle Type 60 x 90 ; 5



April 1992

Stiffness measured @ 3.436 Nm torque load

Load torque opposing flexator 2

# Dual Flexator Stiffness Graph

Muscle Type 60 x 90 ; 5

|   |        |        |        |        |        |        |        |        |
|---|--------|--------|--------|--------|--------|--------|--------|--------|
| 0 | 0      | 0.1273 | 0.2291 | 0.2643 | 0.2864 | 0.2864 | 0.2864 | 0.3818 |
| 1 | 0.0251 | 0.0446 | 0.0573 | 0.0799 | 0.1227 | 0.2021 | 0.2643 | 0.2643 |
| 2 | 0.044  | 0.0446 | 0.0545 | 0.0799 | 0.1041 | 0.1074 | 0.1185 | 0.1185 |
| 3 | 0.1108 | 0.0687 | 0.0818 | 0.0818 | 0.0881 | 0.1011 | 0.1185 | 0.1185 |
| 4 | 0.2454 | 0.1273 | 0.1145 | 0.1273 | 0.1145 | 0.1041 | 0.0955 | 0.0955 |
| 5 | 0.6873 | 0.3124 | 0.1494 | 0.1494 | 0.1432 | 0.1562 | 0.1145 | 0.1145 |
| 6 | 0.6873 | 0.4909 | 0.4295 | 0.2643 | 0.2021 | 0.2148 | 0.1909 | 0.1909 |

Flexator 2 (Pressure bar g)


0 1 2 3 4 5 6

Flexator 1 (Pressure bar g)

April 1992

Stiffness Measured @ 3.436 Nm Load Torque

Load Torque Acting on Muscle 2



**APPENDIX K : ACSL SIMULATION OF THE DUAL FLEXATOR ACTUATOR**

---

**PROGRAM TO MODEL A DUAL FLEXATOR PNEUMATIC ROTARY ACTUATOR**

!-----Flexator size: 60 x 90 (Stroke = ± 124 deg)

**INITIAL**

!-----Run duration, torque load and inertia

CONSTANT TSTP = 10, TL = 0.0, JM = 0.26, PI = 3.14159

!-----Actuator body radii and hose radius when full

CONSTANT R1 = 31.75E-03, R2 = 14E-03, RH = 18.46E-03

!-----Flexator wrap around angle when fully vented

CONSTANT GA = 2.827

!-----Ratio determining the movement of the flexator &

!-----and the movement of the inner drive shaft.

CONSTANT X = 3.3

!-----Viscous and static friction constants

CONSTANT B = 0.81, KS = 1.35

!-----Potentiometer gain and gas constants

CONSTANT KP = 0.8426, K = 0.040418, R = 287

!-----Pressures & temperatures of supply and atmosphere

CONSTANT PA = 101325, PS = 701325, TA = 293, TS = 293

!-----Initial values of chamber pressure & temperature

CONSTANT P1INIT = 370000, P2INIT = 370000, T1 = 293, T2 = 293

!-----Effective valve orifice areas

CONSTANT A1 = 0.14E-06, A2 = 0.14E-06

!-----Critical pressure ratios for chambers 1 & 2

CONSTANT B1 = 0.15, B2 = 0.15

!-----Initial starting conditions (step of 75 deg)

CONSTANT THEDIC = 0.0, THEIC = 0.0, TZ = 0.0, KT = 1.3090

!-----Initial values of chamber volumes & gas masses

V1INIT = (0.0308E-05\*((THEIC+2.1642)/PI)\*180))+1.6653E-05

V2INIT = (0.0308E-05\*((2.1642-THEIC)/PI)\*180))+1.6653E-05

M1INIT = (P1INIT\*V1INIT)/(R\*T1)

M2INIT = (P2INIT\*V2INIT)/(R\*T2)

!-----Boundary conditions for implementing the flow factor

CONSTANT LL = 0.2404, UL = 2.1642, CF = 41.58

!-----Set up deadband upper and lower limits

CONSTANT DLL = -0.01, DUL = 0.01

!-----Communication intervals

CINTERVAL CINT = 0.01

NSTEPS NSTP = 1

MAXTERVAL MAXT = 0.005

!-----Prepare the output variables

PREPAR(T, THE, THED, THEDD, THER, THEM, ERROR, TQ, DP, P1, P2, &  
V1, V2, M1, M2, FD, FS, M1DOT, M2DOT, KF, MT, TF1, TF2)

END\$ "OF INITIAL"

DYNAMIC

DERIVATIVE

!-----Calculate the angular acceleration and velocity

THEDD = (TQ-FD-FS-TL)/JM

THED = INTEG(THEDD, THEDIC)

!-----Calculate and limit the angular displacement

THE = LIMINT(THED, THEIC, -2.1642, 2.1642)

!-----Calculate the actuator torque

TQ = TF1-TF2

TF1=(P1G\*R1\*R2)/(2\*COS((PI-GA)/2))\*((PI\*RH)-(R1\*((GA-AL1)/2))&  
\*(1-COS(AL1))

TF2=(P2G\*R1\*R2)/(2\*COS((PI-GA)/2))\*((PI\*RH)-(R1\*((GA-AL2)/2))&  
\*(1-COS(AL2))

!-----Calculate the gauge pressures

P1G = P1-101325

P2G = P2-101325

!-----Calculate the angle from the clamp to breakaway point

AL1 = GA-((THE+2.1642)/X)

AL2 = GA-((2.1642-THE)/X)

!-----Calculate the static and viscous frictional torques

FD = B\*THED

FS = SIGN(1.0, THED)\*ABS(F1+F2)

F1 = (THE+2.1642)/KS

F2 = (-2.1642+THE)/KS

!-----Calculate the differential pressure

DP = P1-P2

```

!-----Limit the pressure of P1 to be between 1 and 7 bar
PROCEDURAL(P1 = M1, M2, V1, V2)
P1 = (M1*R*T1)/V1
IF (P1 .GT. 701325) P1 = 701325
IF (P1 .LT. 101325) P1 = 101325

!-----Limit the pressure of P2 to be between 1 and 7 bar
P2 = (M2*R*T2)/V2
IF (P2 .GT. 701325) P2 = 701325
IF (P2 .LT. 101325) P2 = 101325
END$ "OF PROCEDURAL"

!-----Calculate the volume of the actuator chambers
V1 = ((0.0308E-05*((THE+2.1642)/PI)*180))+1.6653E-05
V2 = ((0.0308E-05*((2.1642-THE)/PI)*180))+1.6653E-05

!-----Calculate the mass of the gas in each chamber
M1 = INTEG((Y*M1DOT), M1INIT)
M2 = INTEG((-1)*Y*M2DOT), M2INIT)

!-----Use the sign of the error to correct mass flows
Y = SIGN(1.0, ERROR)

!-----Calculate mass flow rates of chamber 1, for given states
M1ADOT=KF*((K*A1*PS)/(SQRT(TS)))*(SQRT(1-(((P1/PS)-B1)/(1-B1))**2)))
M1BDOT=KF*((K*A1*PS)/(SQRT(TS)))
M1CDOT=KF*((K*A1*P1)/(SQRT(T1)))*(SQRT(1-(((PA/P1)-B1)/(1-B1))**2)))
M1DDOT=KF*((K*A1*P1)/(SQRT(T1)))

!-----Select the correct mass flow function for chamber 1
!-----and set up the amount of deadband space
IF (ERROR .LT. DLL) THEN
M1DOT = RSW((PA/P1) .GT. B1, M1CDOT, M1DDOT)
ELSE IF (ERROR .GT. DUL) THEN
M1DOT = RSW((P1/PS) .GT. B1, M1ADOT, M1BDOT)
ELSE
M1DOT = 0.0 ; END IF

!-----Calculate mass flow rates of chamber 2, for given states
M2ADOT=KF*((K*A2*P2)/(SQRT(T2)))*(SQRT(1-(((PA/P2)-B2)/(1-B2))**2)))
M2BDOT=KF*((K*A2*P2)/(SQRT(T2)))
M2CDOT=KF*((K*A2*PS)/(SQRT(TS)))*(SQRT(1-(((P2/PS)-B2)/(1-B2))**2)))
M2DDOT=KF*((K*A2*PS)/(SQRT(TS)))

!-----Select the correct mass flow function for chamber 2
!-----and set up the amount of deadband space
IF (ERROR .LT. DLL) THEN
M2DOT = RSW((P2/PS) .GT. B2, M2CDOT, M2DDOT)

```

```
ELSE IF (ERROR .GT. DUL) THEN
M2DOT = RSW((PA/P2) .GT. B2, M2ADOT, M2BDOT)
ELSE
M2DOT = 0.0 ; END IF

!-----Calculate the flow factor based on % PWM mark time
!-----This varies from 24% to 100%
KF = ((0.9372*MT)+14.801)/100

!-----Calculate the % mark time of the PWM signal
!-----This varies from 10% to 90%, ie a maximum when error
!-----is a maximum. Defined by the angular limits and CF.
MT = (BOUND(LL, UL, ABS(ERROR)))*CF

!-----Calculate the required angle (volts)
THER = KT*STEP(TZ)

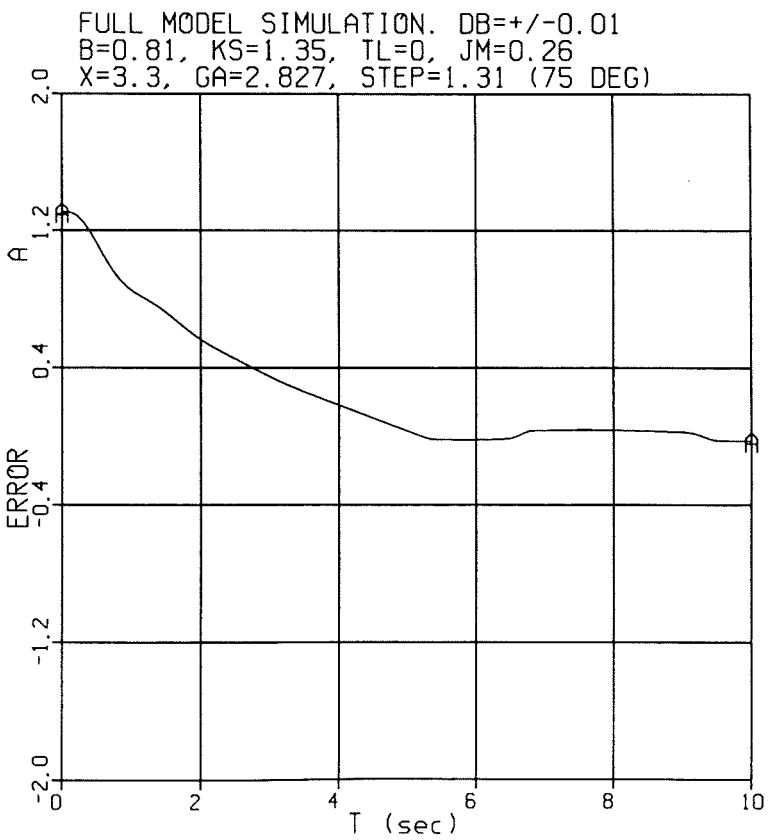
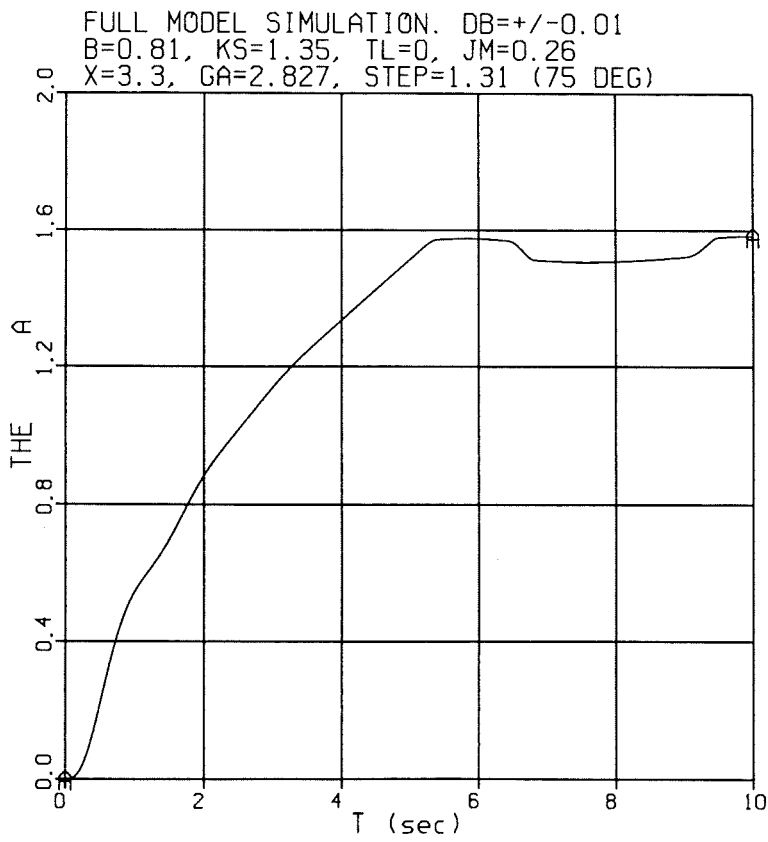
!-----Calculate the measured angle (volts)
THEM = KP*THE

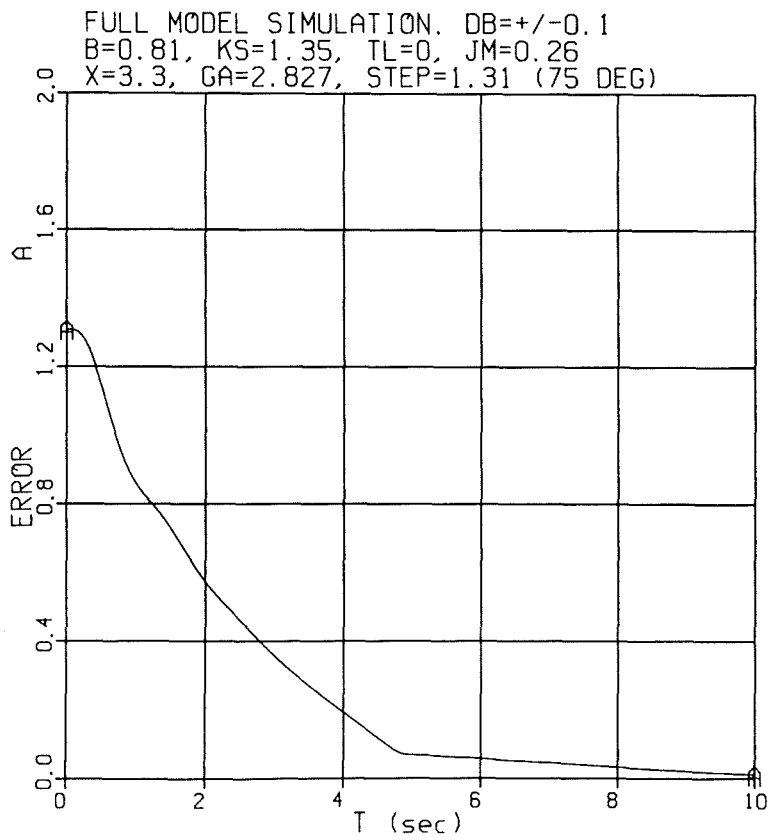
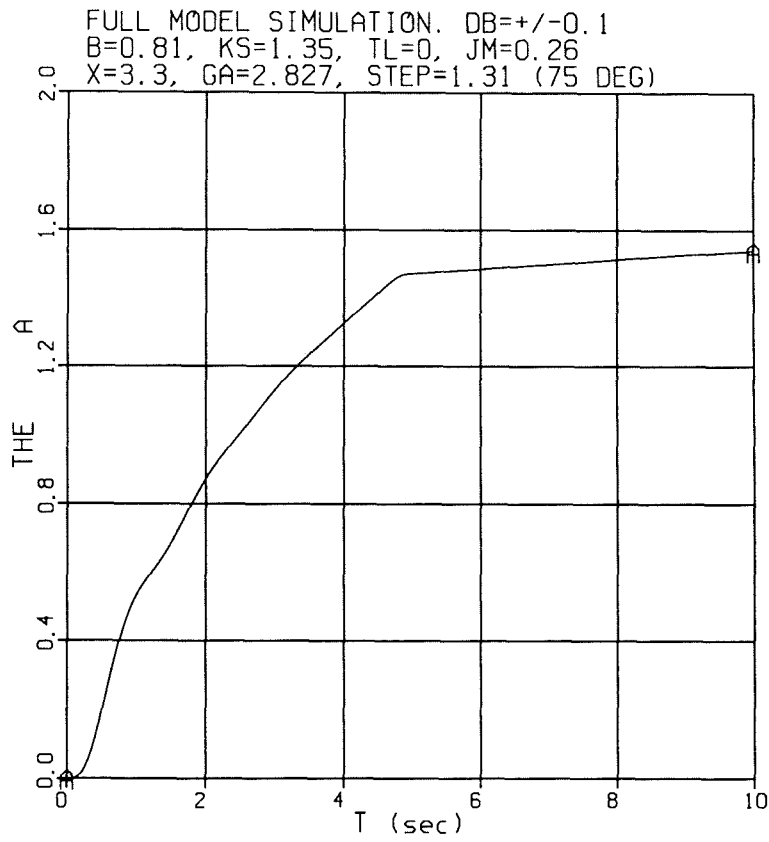
!-----Calculate the error signal (volts)
ERROR = (THER-THEM)

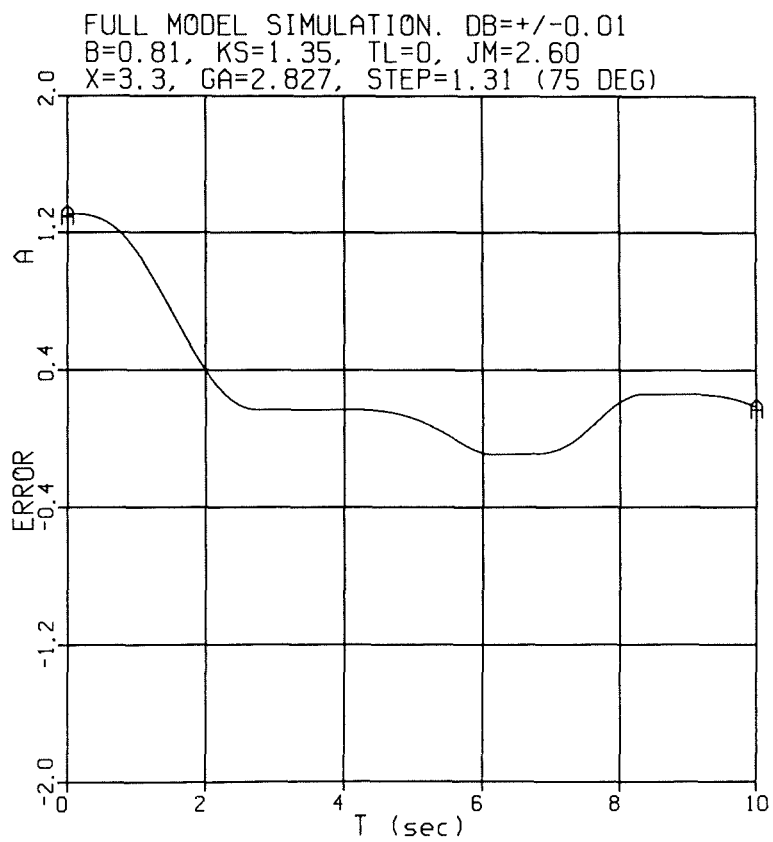
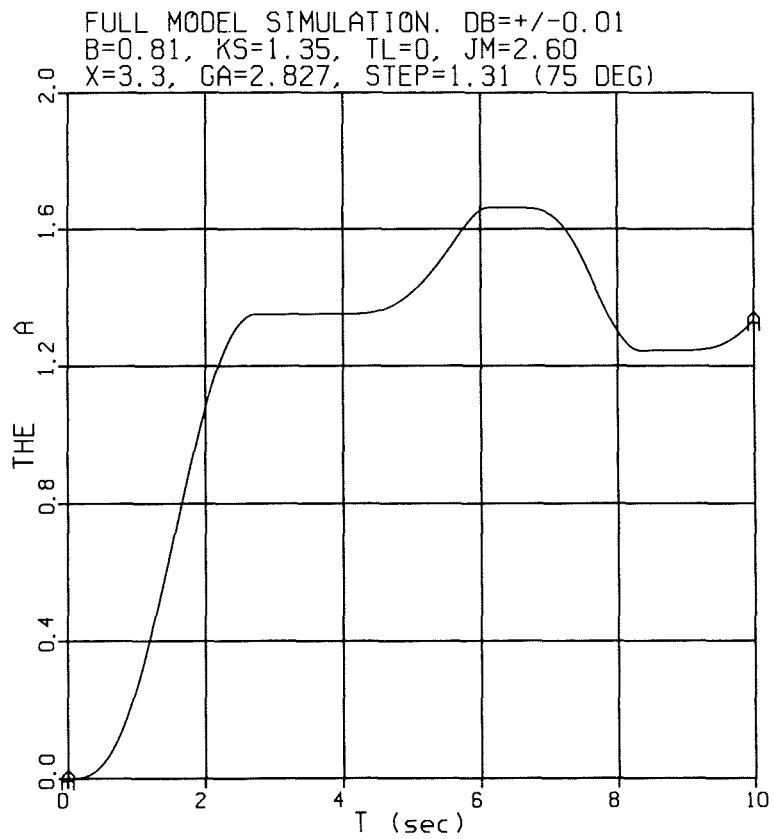
END$ "OF DERIVATIVE"

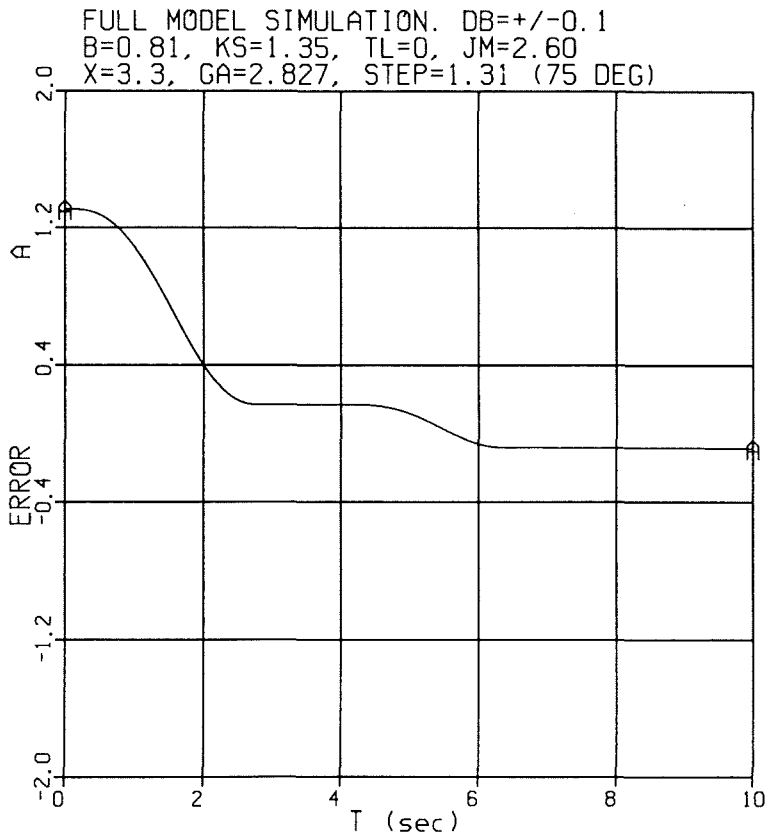
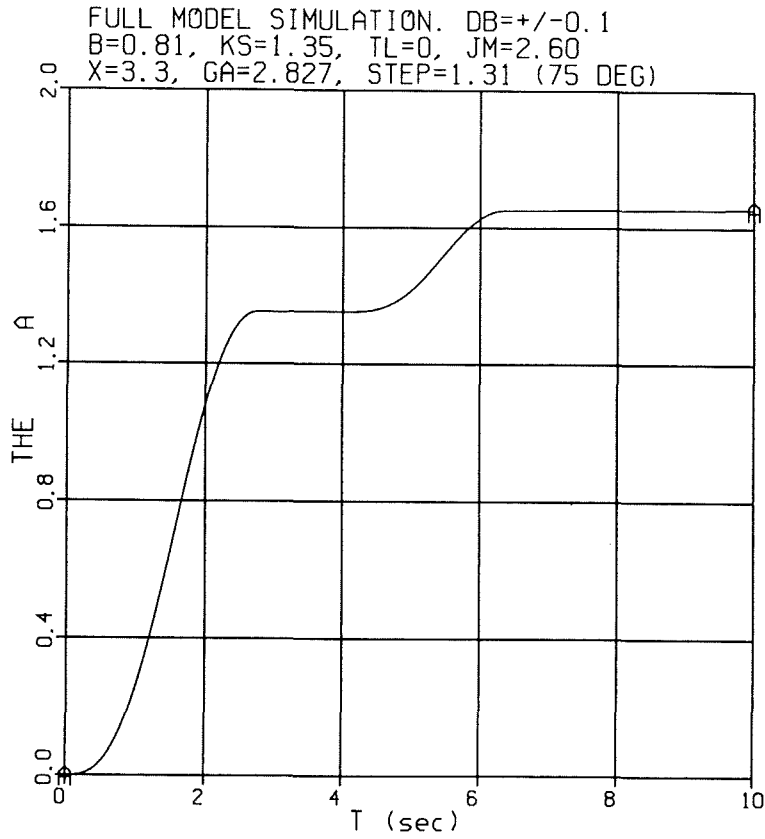
TERMT (T .GE. TSTP)
END$ "OF DYNAMIC"
END$ "OF PROGRAM"
```





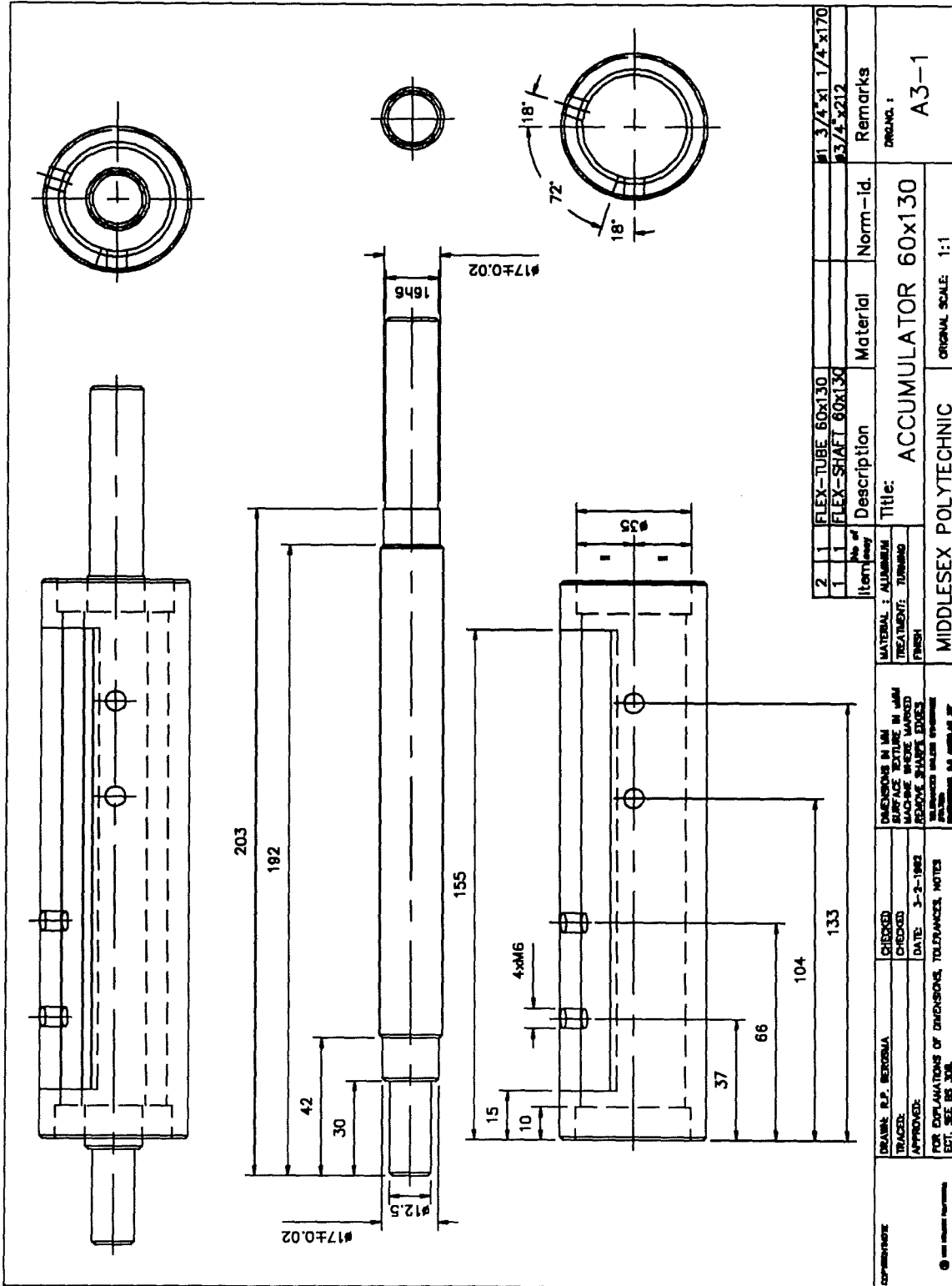


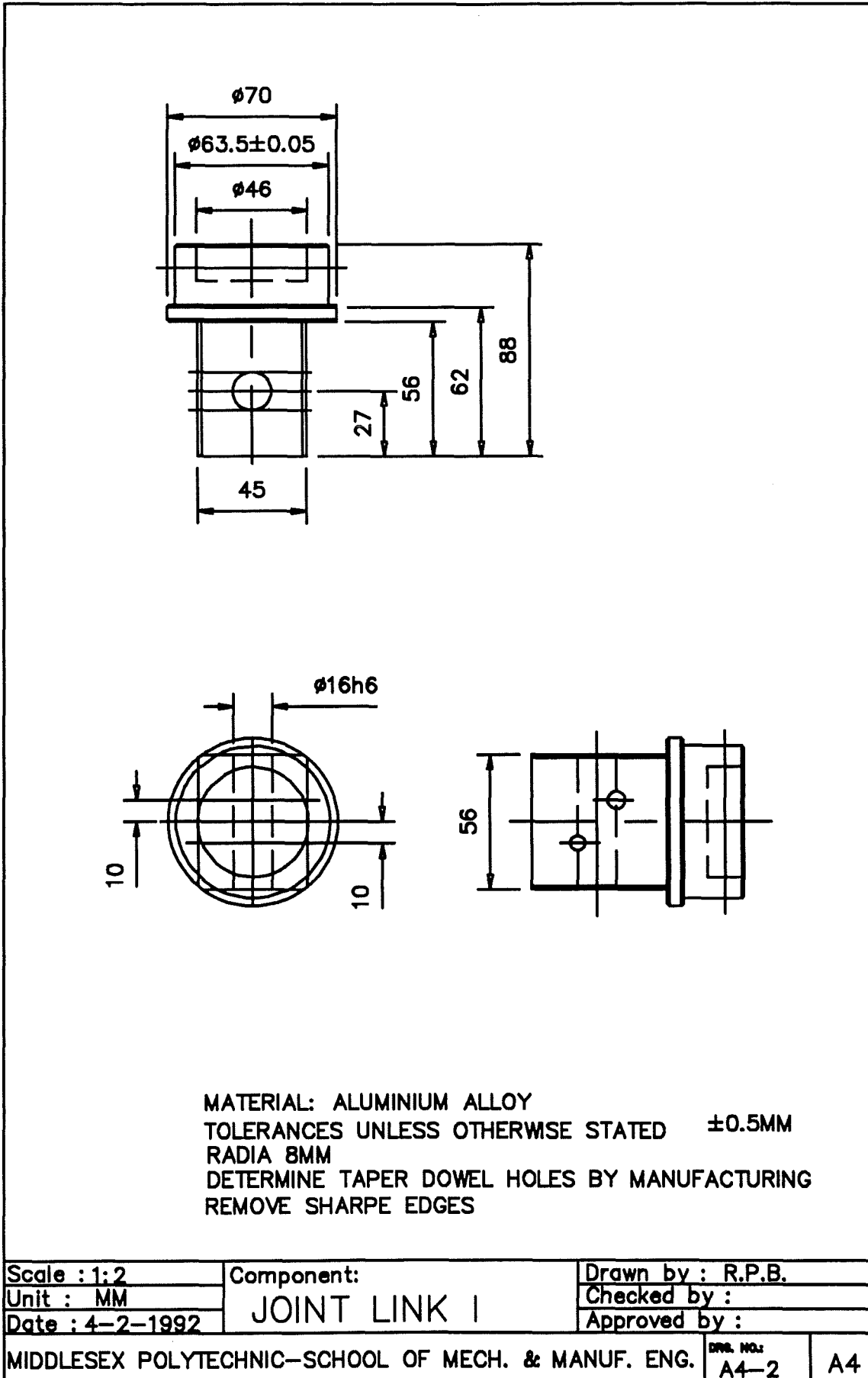


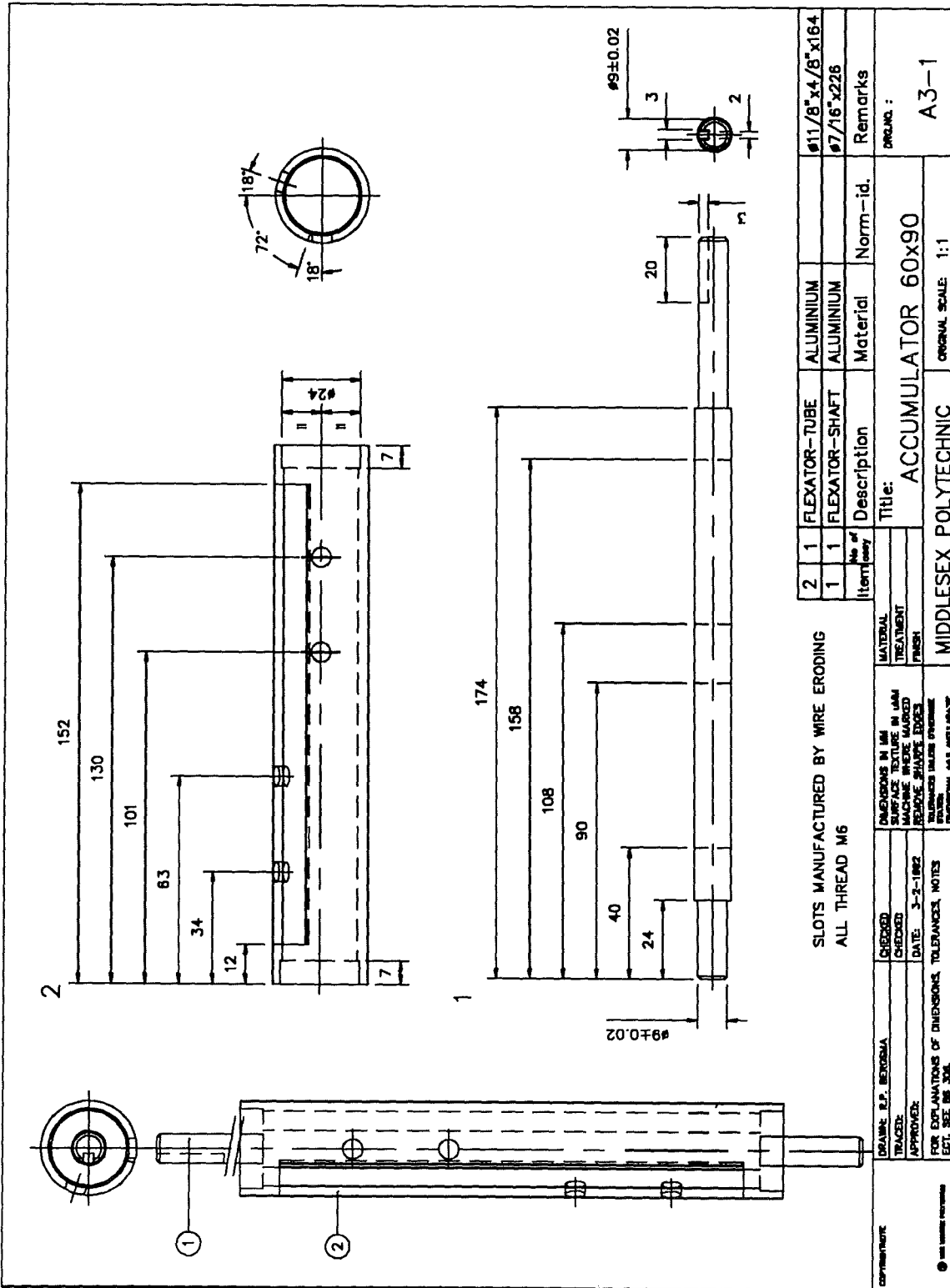




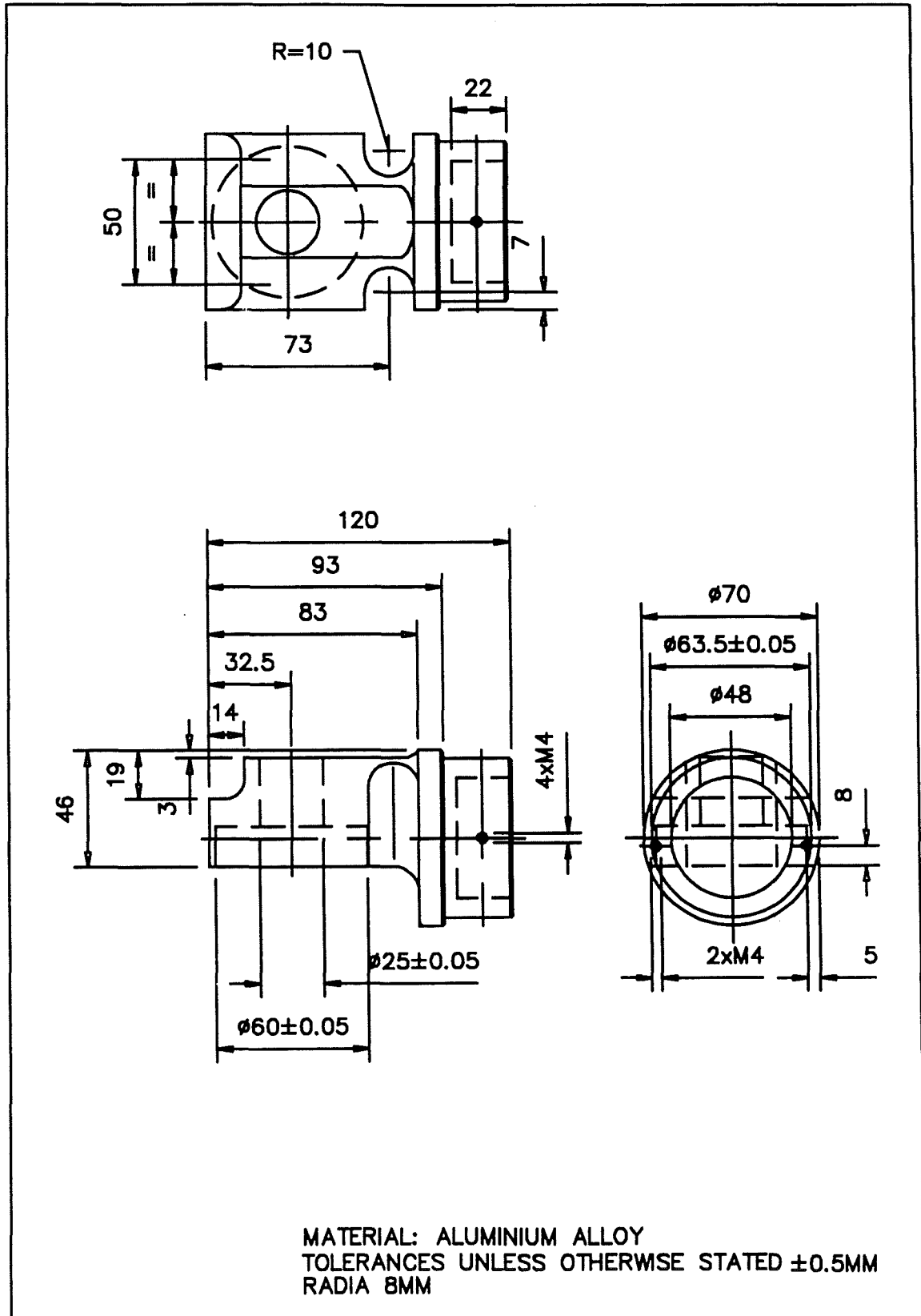
**APPENDIX L : WORKING DRAWINGS OF THE FIRST PROTOTYPE**



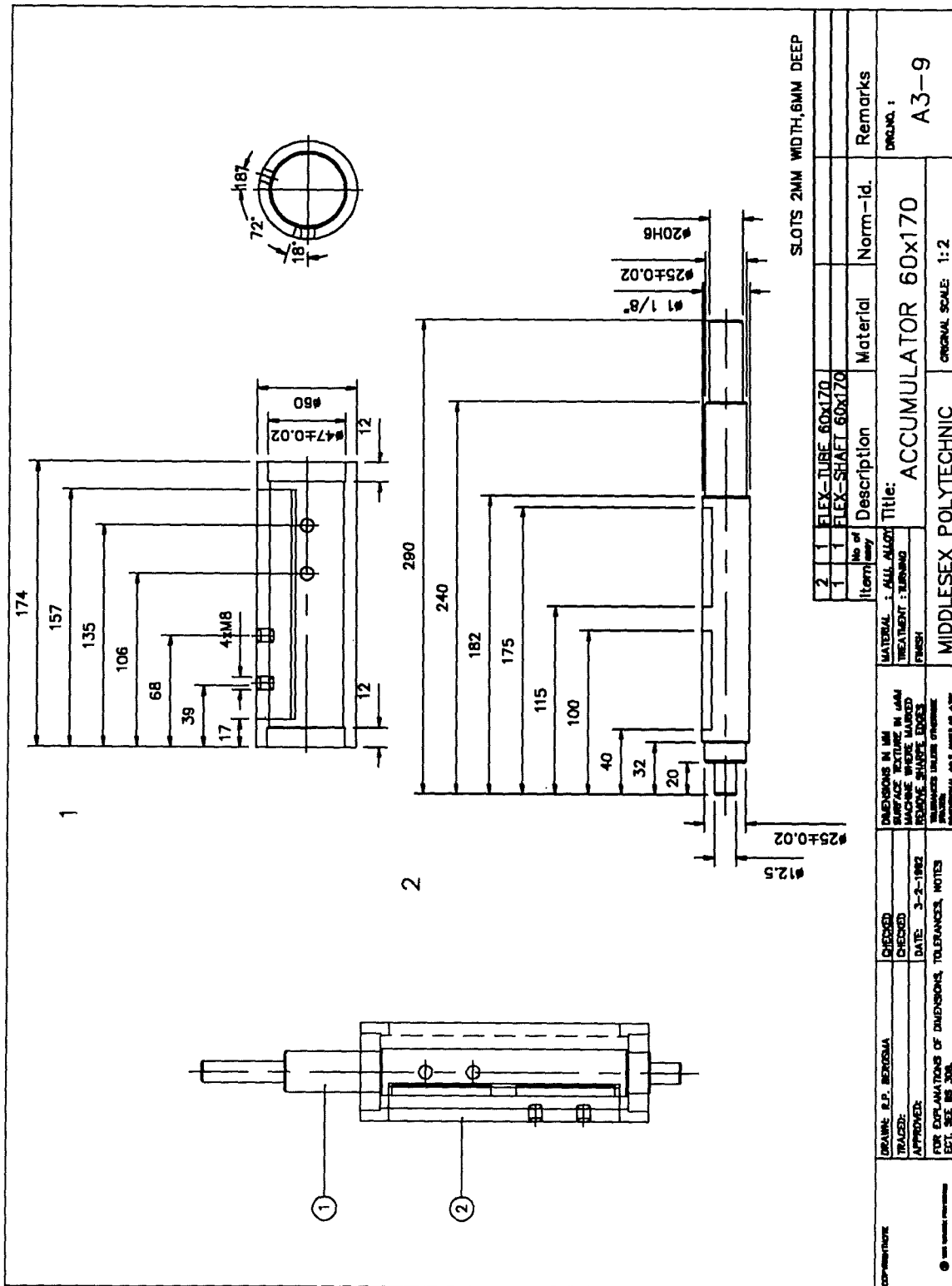


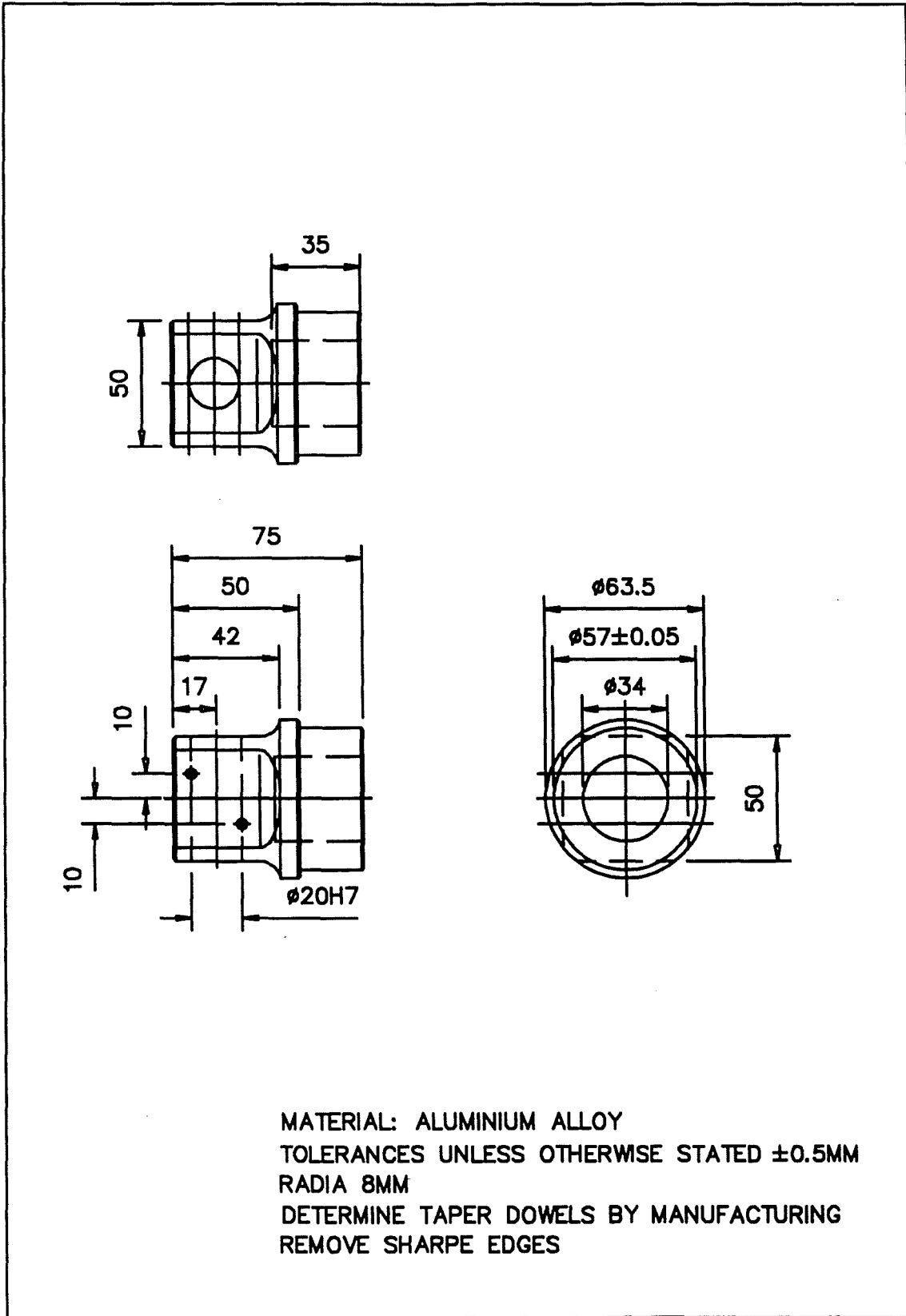







|   |                                    |                   |    |
|---|------------------------------------|-------------------|----|
| Scale : 1:2   | Component:<br><b>JOINT LINK II</b> | Drawn by : R.P.B. |    |
| Unit : MM   |                                    | Checked by :      |    |
| Date : 3-2-1992                                     |                                    | Approved by :     |    |
| MIDDLESEX POLYTECHNIC-SCHOOL OF MECH. & MANUF. ENG. |                                    | DRG. NO. A4-8     | A4 |





MATERIAL: ALUMINIUM ALLOY  
 TOLERANCES UNLESS OTHERWISE STATED ±0.5MM  
 RADIA 8MM  
 DETERMINE TAPER DOWELS BY MANUFACTURING  
 REMOVE SHARPE EDGES

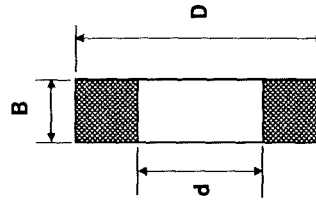
|   |                                     |                    |
|---|-------------------------------------|--------------------|
| Scale : 1:2   | Component:<br><b>JOINT LINK III</b> | Drawn by : R.P.B.  |
| Unit : MM   |                                     | Checked by :       |
| Date : 3-2-1992                                     |                                     | Approved by :      |
| MIDDLESEX POLYTECHNIC-SCHOOL OF MECH. & MANUF. ENG. |                                     | DRG. NO.:<br>A4-10 |
|   |                                     | A4                 |



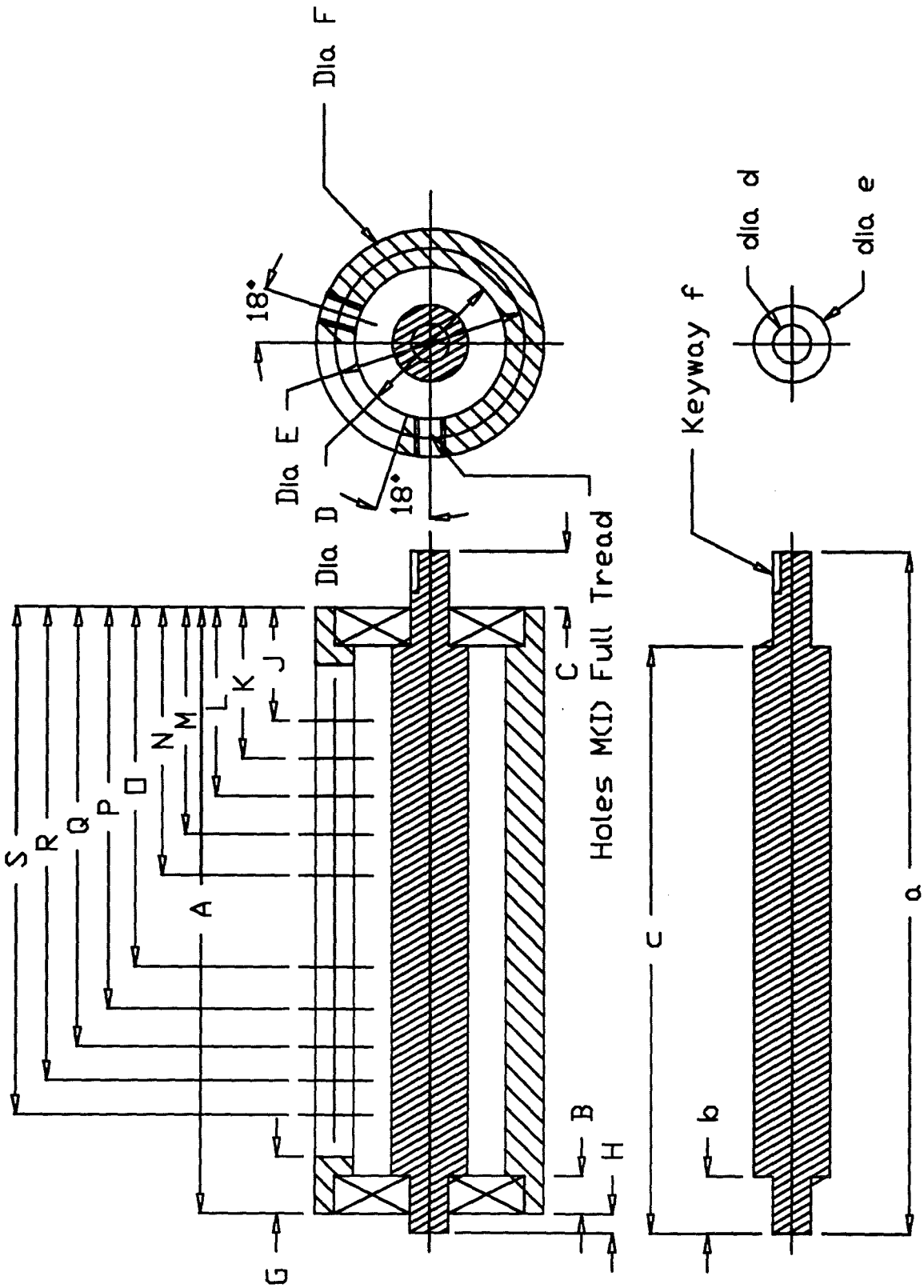
**APPENDIX M : DUAL FLEXATOR ACTUATOR DESIGN TABLES**

---

| Nov '91   | Outer Tube Dimensions |    |    |        |    |        |    |    |   |    |    |    |    |     |     | Inner Shaft Dimensions |     |     |     |     |     |        |        |        |       |
|-----------|-----------------------|----|----|--------|----|--------|----|----|---|----|----|----|----|-----|-----|------------------------|-----|-----|-----|-----|-----|--------|--------|--------|-------|
|           | Muscle Type           | A  | B  | C      | øD | øE     | øF | G  | H | I  | J  | K  | L  | M   | N   | O                      | P   | Q   | R   | S   | a   | b      | c      | ød     | øe    |
| 42 x 90   | 128                   | 7  | 17 | 7/8"   | 24 | 11/8"  | 12 | 20 | 6 | 34 | 49 | /  | /  | /   | /   | /                      | /   | /   | 79  | 94  | 165 | 27     | 141    | 7      | 7/16" |
| 60 x 90   | 164                   | 7  | 17 | 7/8"   | 24 | 11/8"  | 12 | 20 | 6 | 34 | /  | 63 | /  | /   | /   | /                      | /   | 101 | 130 | 201 | 27  | 177    | 7      | 7/16"  |       |
| 83 x 90   | 210                   | 7  | 17 | 7/8"   | 24 | 11/8"  | 12 | 20 | 6 | 34 | /  | /  | 83 | /   | /   | /                      | 127 | 176 | 247 | 27  | 223 | 7      | 7/16"  |        |       |
| 102 x 90  | 248                   | 7  | 17 | 7/8"   | 24 | 11/8"  | 12 | 20 | 6 | 34 | /  | 63 | /  | 102 | 146 | /                      | 185 | 214 | 285 | 27  | 261 | 7      | 7/16"  |        |       |
| 42 x 130  | 134                   | 10 | 22 | 1 1/4" | 35 | 1 3/4" | 15 | 20 | 6 | 37 | 52 | /  | /  | /   | /   | /                      | /   | 82  | 97  | 176 | 30  | 144    | 15     | 3/4"   |       |
| 60 x 130  | 170                   | 10 | 22 | 1 1/4" | 35 | 1 3/4" | 15 | 20 | 6 | 37 | /  | 66 | /  | /   | /   | /                      | 104 | 133 | 212 | 30  | 180 | 15     | 3/4"   |        |       |
| 83 x 130  | 216                   | 10 | 22 | 1 1/4" | 35 | 1 3/4" | 15 | 20 | 6 | 37 | /  | /  | 86 | /   | /   | 130                    | 179 | 258 | 30  | 226 | 15  | 3/4"   |        |        |       |
| 102 x 130 | 254                   | 10 | 22 | 1 1/4" | 35 | 1 3/4" | 15 | 20 | 6 | 37 | /  | 66 | /  | 105 | 149 | /                      | 188 | 217 | 296 | 30  | 264 | 15     | 3/4"   |        |       |
| 42 x 170  | 138                   | 12 | 27 | 1 3/4" | 47 | 60     | 17 | 20 | 8 | 39 | 54 | /  | /  | /   | /   | /                      | /   | 84  | 99  | 185 | 32  | 146    | 23     | 1 1/8" |       |
| 60 x 170  | 174                   | 12 | 27 | 1 3/4" | 47 | 60     | 17 | 20 | 8 | 39 | /  | 68 | /  | /   | /   | /                      | 106 | 135 | 221 | 32  | 182 | 23     | 1 1/8" |        |       |
| 83 x 170  | 220                   | 12 | 27 | 1 3/4" | 47 | 60     | 17 | 20 | 8 | 39 | /  | /  | 88 | /   | /   | 132                    | 181 | 267 | 32  | 228 | 23  | 1 1/8" |        |        |       |
| 102 x 170 | 258                   | 12 | 27 | 1 3/4" | 47 | 60     | 17 | 20 | 8 | 39 | /  | 68 | /  | 107 | 151 | /                      | 190 | 219 | 305 | 32  | 266 | 23     | 1 1/8" |        |       |



| Actuator Type | Bearing Type | d  | D  | B  | Keyway f<br>(W x T x L) |
|---------------|--------------|----|----|----|-------------------------|
| 90            | 609-2Z       | 9  | 24 | 7  | 3 x 3 x 12              |
| 130           | 6003-2Z      | 17 | 35 | 10 | 5 x 5 x 16              |
| 170           | 6005-2Z      | 25 | 47 | 12 | 8 x 7 x 20              |





**APPENDIX N : CONTROLLER HARDWARE DESCRIPTION**

## PORT DESCRIPTION OF INTEL 8051

### PORT 1

P1 is used for switching the solenoid valves via the two multi-plexers 74LS154. The following listing shows which binary combination must be written to P1 to switch the corresponding valve:

#### Joint 1 (arm up/down):

|                              |    |                      |
|------------------------------|----|----------------------|
| Inlet valve - cylinder 1.1   | == | port P1 = #0000xxxxB |
| Exhaust valve - cylinder 1.2 | == | port P1 = #xxxx0000B |
| Inlet valve - cylinder 1.2   | == | port P1 = #0001xxxxB |
| Exhaust valve - cylinder 1.1 | == | port P1 = #xxxx0001B |

#### Joint 2 (shoulder ±):

|                            |    |                      |
|----------------------------|----|----------------------|
| Inlet valve - muscle 2.1   | == | port P1 = #0010xxxxB |
| Exhaust valve - muscle 2.2 | == | port P1 = #xxxx0010B |
| Inlet valve - muscle 2.2   | == | port P1 = #0011xxxxB |
| Exhaust valve - muscle 2.1 | == | port P1 = #xxxx0011B |

#### Joint 3 (mode change ±):

|                            |    |                      |
|----------------------------|----|----------------------|
| Inlet valve - muscle 3.1   | == | port P1 = #0100xxxxB |
| Exhaust valve - muscle 3.2 | == | port P1 = #xxxx0100B |
| Inlet valve - muscle 3.2   | == | port P1 = #0101xxxxB |
| Exhaust valve - muscle 3.1 | == | port P1 = #xxxx0101B |

#### Joint 4 (elbow ±):

|                            |    |                      |
|----------------------------|----|----------------------|
| Inlet valve - muscle 4.1   | == | port P1 = #0110xxxxB |
| Exhaust valve - muscle 4.2 | == | port P1 = #xxxx0110B |
| Inlet valve - muscle 4.2   | == | port P1 = #0111xxxxB |
| Exhaust valve - muscle 4.1 | == | port P1 = #xxxx0111B |



**Joint 5 (Wrist/End Effector extension ±):**

Inlet valve - cylinder 5.1 == port P1 = #1000xxxxB  
 Exhaust valve - cylinder 5.2 == port P1 = #xxxx1000B  
 Inlet valve - cylinder 5.2 == port P1 = #1001xxxxB  
 Exhaust valve - cylinder 5.1 == port P1 = #xxxx1001B

Note: Port P1 = #1xxxxxxxB -- Pin1.7 = 1  
           #0xxxxxxxB -- Pin1.7 = 0  
           #x1xxxxxxxB -- Pin1.6 = 1  
           :  
           #xxxxxxx0B -- Pin1.0 = 0

**PORT 2**

P2 is used to read the keypad value and to output the demultiplexer and data selector input to select between the different A/D converters.

Pin P2.0 = A0 dataselector and demultiplexer  
 Pin P2.1 = A1 dataselector and demultiplexer  
 Pin P2.2 = A2 dataselector and demultiplexer  
 Pin P2.3 = /chip select for dataselector and demultiplexer  
 Pin P2.4 = A0 keyboard  
 Pin P2.5 = A1 keyboard  
 Pin P2.6 = A2 keyboard  
 Pin P2.7 = A3 keyboard

**PORT 3**

Not all pins from P3 are used. The unused pins are lined to connector B, so that they may be used for other functions.

Pin P3.0 (RXD) = the serial data bytes from the A/D converter enters through this port.  
 Pin P3.1 (TXD) = this port outputs the shift clock.  
 Pin P3.2 (/INT0) = external interrupt -- emergency switch high priority (low level activated).  
 Pin P3.3 (/INT1) = external interrupt -- data available signal of the user interface (low level activated).

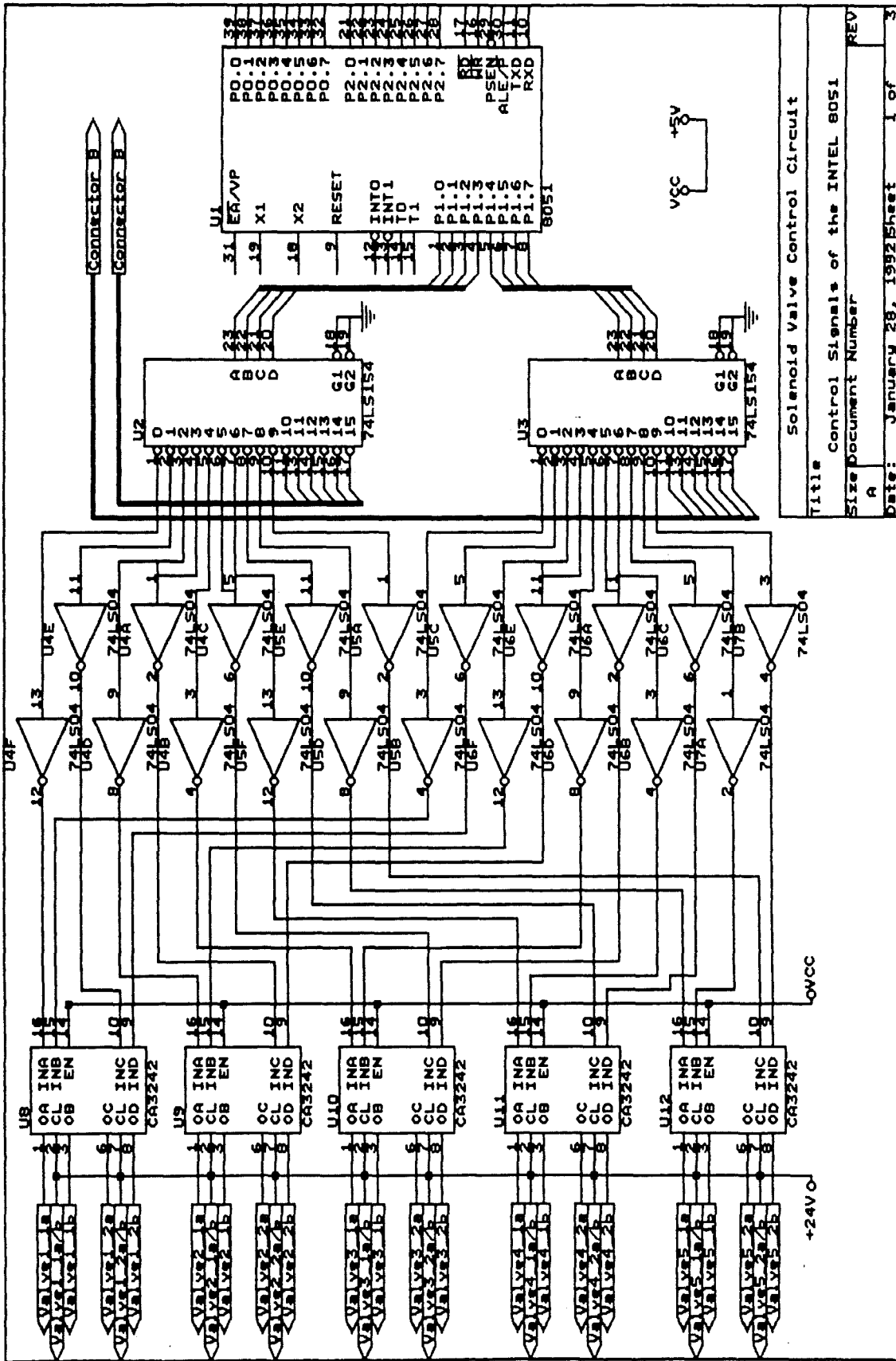
## PORT 0

P0 is not used. The pins are wired to connector B, so that they can be used for other functions.

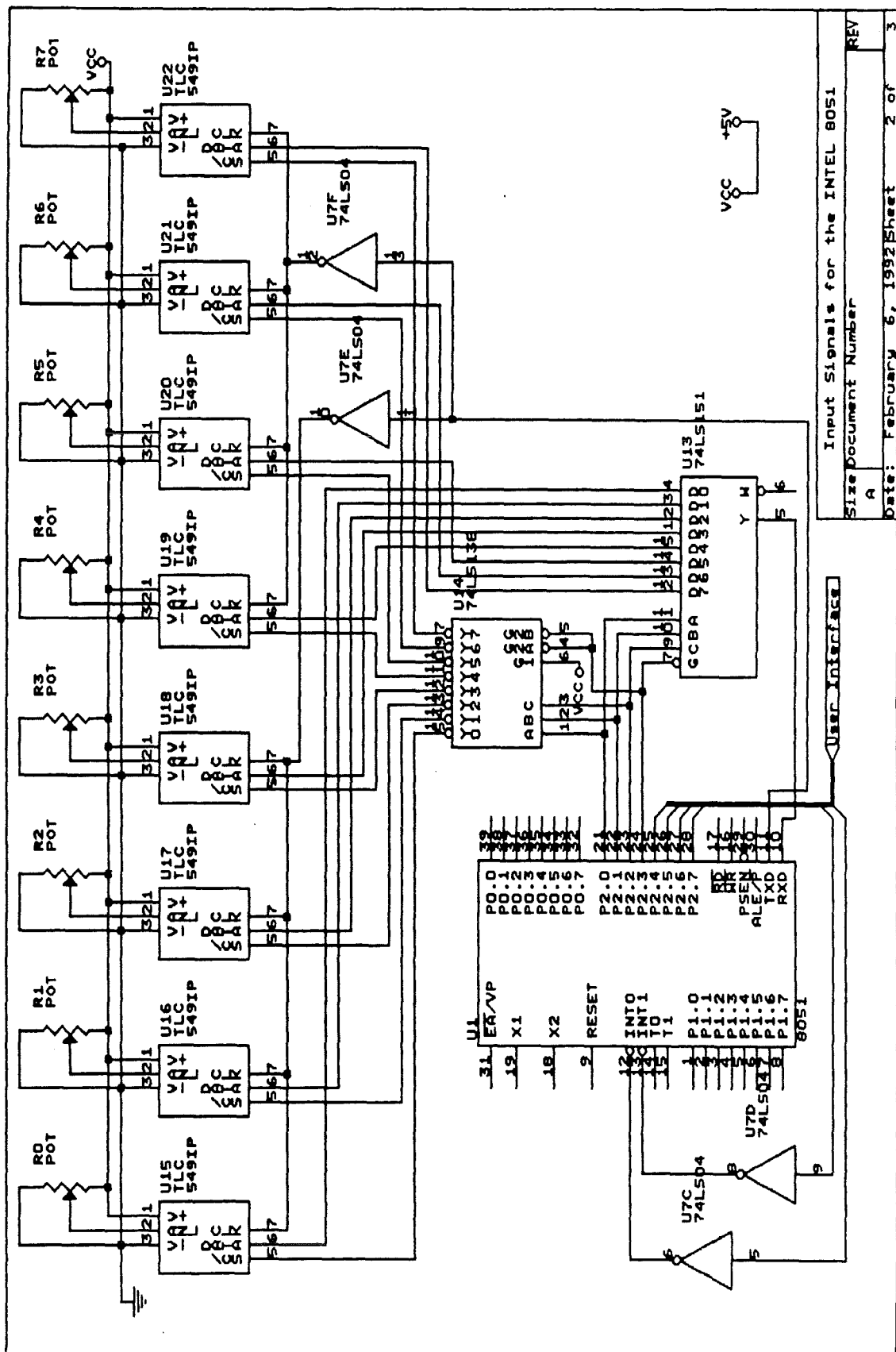
## PIN RST

The reset pin is wired to connector B. After the board was produced, it was discovered that when switching on the supply voltage the INTEL 8051 did not reset automatically and did not initiate the correct program execution. So a reset circuit had to be installed on the PCB. A high on this pin for two machine cycles, while the oscillator is running, resets the device. For program execution a low has to be on the pin. Therefore a capacitor (10F) was soldered between Vcc and RST and a resistor (10K) between GND and RST. This circuit holds the RST pin high for an amount of time that depends on the capacitor value and the rate at which it charges. This modification can be found at the bottom of the board.

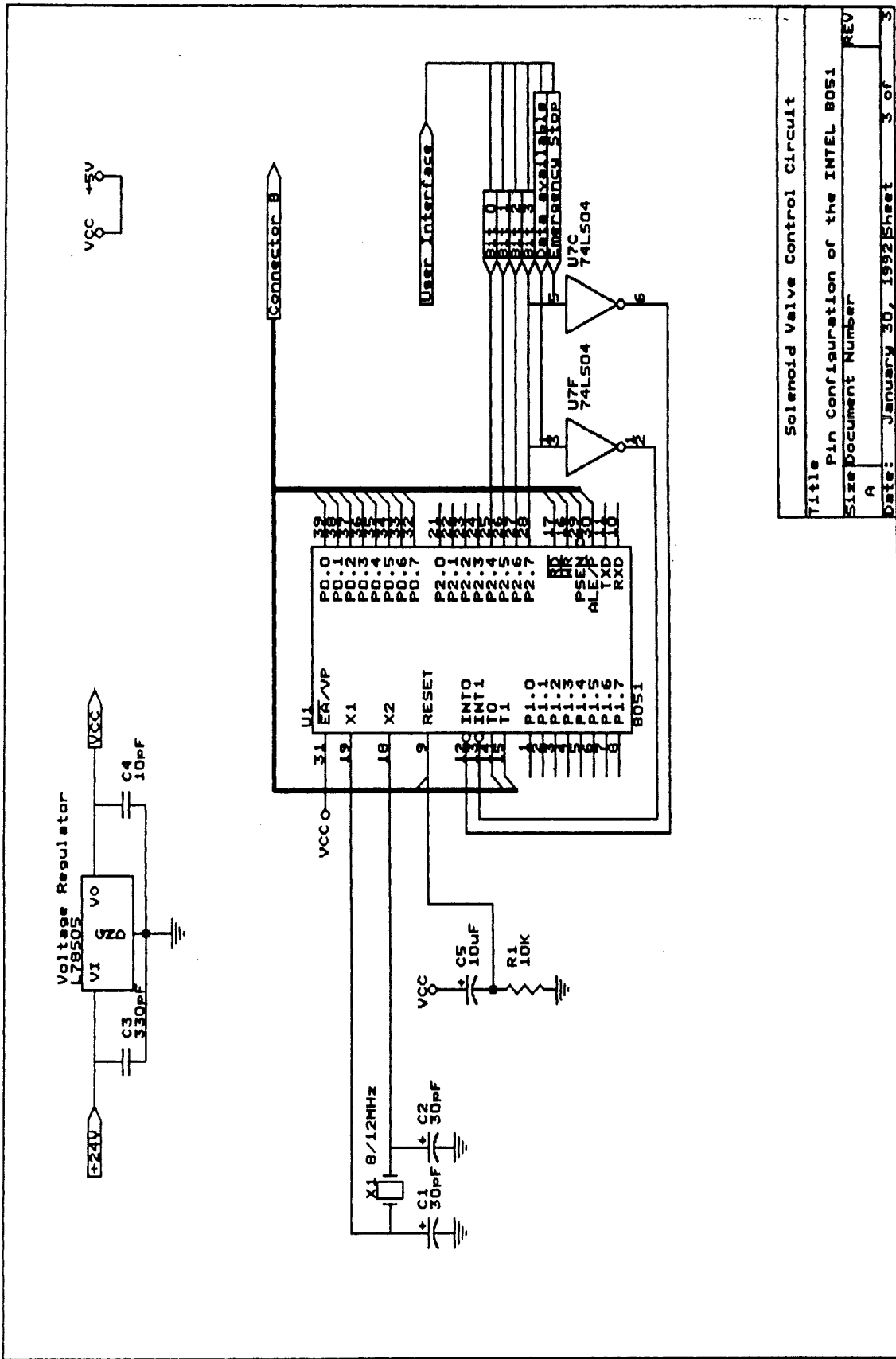
Also the pins ALE and /PSEN are not used on the board. They are wired to connector B.

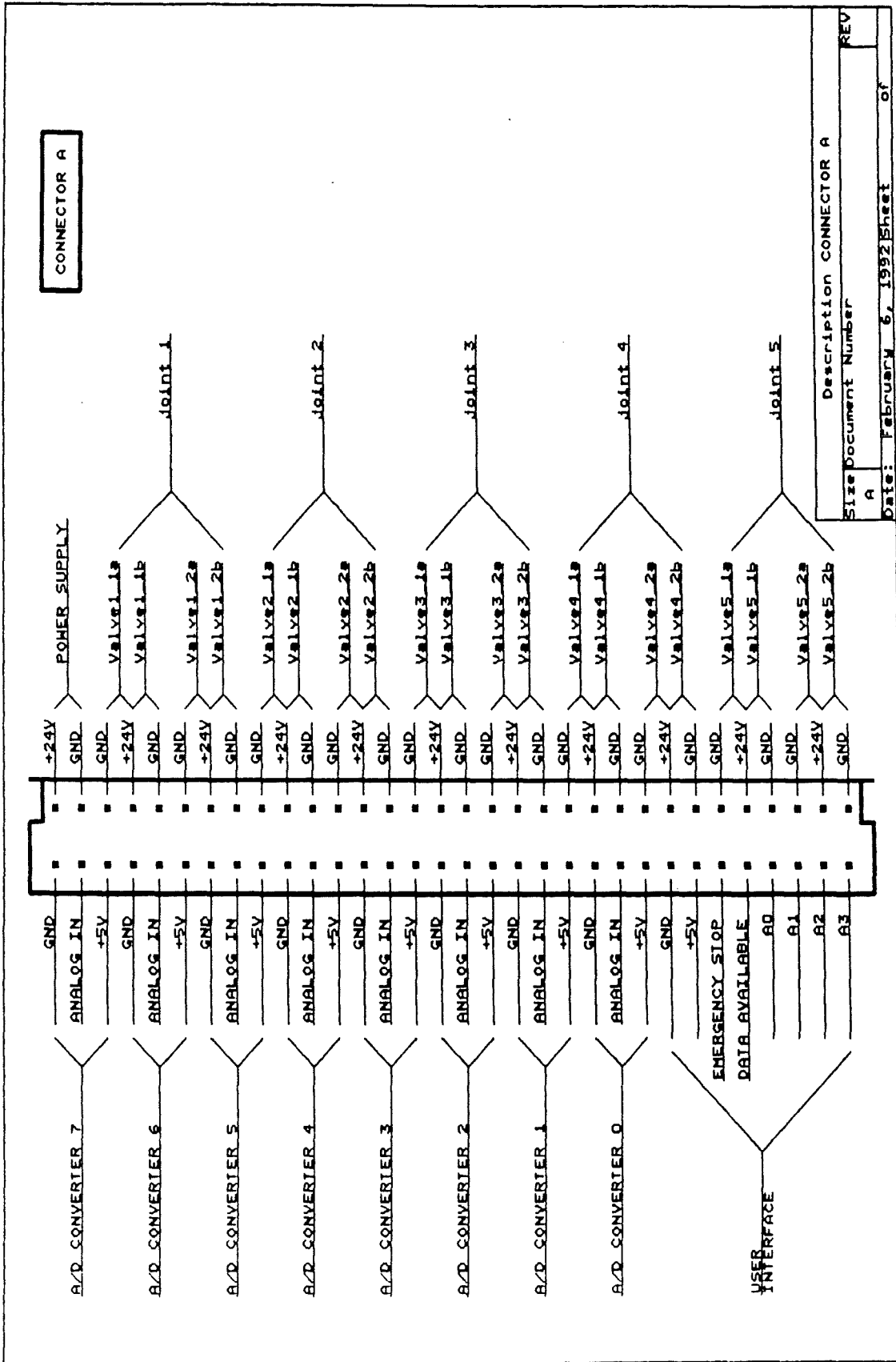


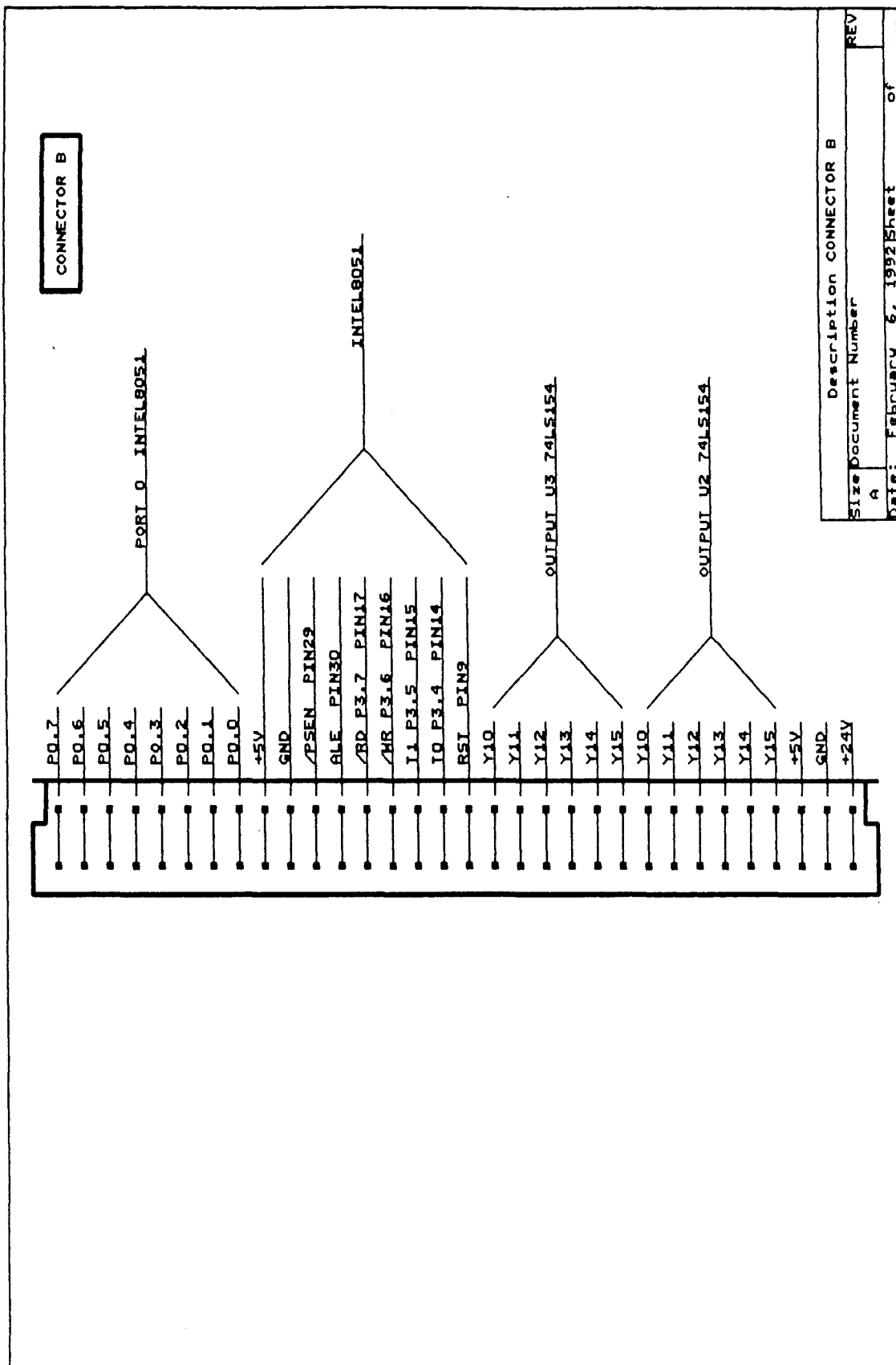
|                 |                  |                                   |
|-----------------|------------------|-----------------------------------|
| Title           |                  | Solenoid Valve Control Circuit    |
| Size            |                  | Control Signals of the INTEL 8051 |
| Document Number |                  | A                                 |
| Date:           | January 28, 1992 | Sheet 1 of 3                      |
| REV             |                  |                                   |

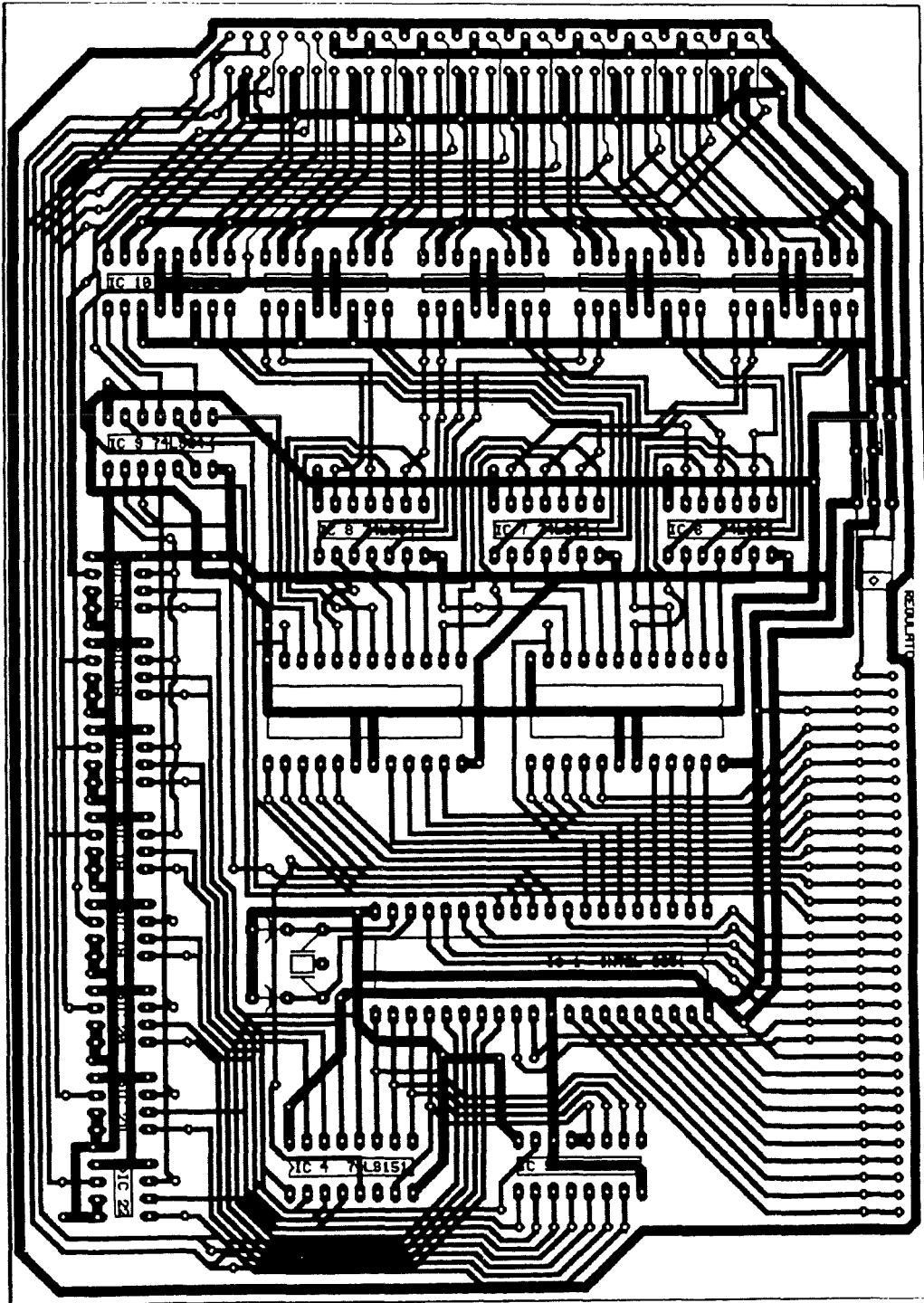


|                                  |              |
|----------------------------------|--------------|
| Input Signals for the INTEL 8051 | REV          |
| Size Document Number             | A            |
| Date: February 6, 1992           | Sheet 2 of 3 |









Layout for the printed circuit board designed with the software package "EASY PC"





**APPENDIX P : ASSEMBLER COMPUTER PROGRAM TO CONTROL THE ARM**

```

name valve
;-----;
; Project      MICRPOCESSOR BASED CONTROL, UNIT
;              FOR A ROBOTIC ARM MOUNTED ON A WHEELCHAIR
;-----;
;
; Name        : VALVE.ASM
; Function    : Control program for a robotic arm
;              mounted on a wheelchair
; Input       : User input via interface,
;              position feedback via A/D-converter
; Output      : Control signals for the solenoid valves
; Author      : Peter Oettinger
;-----;
;*** FUNCTION LOCATIONS ***
;*** 5 different locations for 4 joints **
;F1_0      EQU      30H      ;location 1 for joint 1
;F1_1      EQU      31H      ;location 1 for joint 2
;F1_2      EQU      32H      ;location 1 for joint 3
;F1_3      EQU      33H      ;location 1 for joint 4
;F2_0      EQU      35H      ;location 2 for joint 1
;F2_1      EQU      36H      ;location 2 for joint 2
;F2_2      EQU      37H      ;location 2 for joint 3
;F2_3      EQU      38H      ;location 2 for joint 4
;F3_0      EQU      3AH      ;location 3 for joint 1
;F3_1      EQU      3BH      ;location 3 for joint 2
;F3_2      EQU      3CH      ;location 3 for joint 3
;F3_3      EQU      3DH      ;location 3 for joint 4
;F4_0      EQU      3FH      ;location 4 for joint 1
;F4_1      EQU      40H      ;location 4 for joint 2
;F4_2      EQU      41H      ;location 4 for joint 3
;F4_3      EQU      42H      ;location 4 for joint 4
;F5_0      EQU      43H      ;location 5 for joint 1
;F5_1      EQU      44H      ;location 5 for joint 2
;F5_2      EQU      45H      ;location 5 for joint 3
;F5_3      EQU      46H      ;location 5 for joint 4
;
;*** NOMINAL LOCATION FOR POSITION CONTROL ***
REST0      EQU      47H      ;nominal location for joint 1
REST1      EQU      48H      ;nominal location for joint 2
REST2      EQU      49H      ;nominal location for joint 3
REST3      EQU      4AH      ;nominal location for joint 4
;
;*** DELAY VALUES --> SPEED REGULATION ***
;** different delays for each joint **
SPE_0      EQU      4BH      ;speed for joint 1
SPE_1      EQU      4CH      ;speed for joint 2
SPE_2      EQU      4DH      ;speed for joint 3
SPE_3      EQU      4EH      ;speed for joint 4
SPE_4      EQU      4FH      ;speed for joint 5
SPEED      EQU      50H
;
VX_1       EQU      51H
VX_2       EQU      52H
TOL        EQU      53H
;
DIG        EQU      20H
FLAG       EQU      21H
FLAG_K9    EQU      FLAG.7
;
ORG 0000H

```

```

        LJMPL    init
;*** external interrupt 0 ***
        MOV     P1,    #11111111B    ;switch all valves off
EXE0:   SJMPL    EXE0

        NOP     ;no operation
        NOP
        NOP
        NOP
        NOP
        NOP
        NOP
        NOP
        NOP
        NOP
        NOP
;*** external interrupt 1 ***
        LJMPL    READ

;*** INITIALISE THE SYSTEM ***
;** Initialise Special-Function-Registers **
init:   MOV     IE,    #10000101B    ;enable INT0, INT1
;
;           | |
;           | External Interrupt 0
;           | External Interrupt 1
;
        MOV     IP,    #00000001B    ;INT0 high priority

        MOV     P1,    #11111111B
        MOV     VX_1,  #22H
        MOV     VX_2,  #33H
        MOV     SPE_0, #0FH
        MOV     SPE_1, #0FH
        MOV     SPE_2, #0FH
        MOV     SPE_3, #0FH
        MOV     SPE_4, #0FH

        SETB    P3.2
        SETB    P3.3
        CLR     FLAG_K9
        MOV     SCON,  #10H
        CLR     RI

;*** MAIN ROUTINE ***
;** position control **
;ZZZ:   SJMPL    ZZZ
        MOV     SP,    #07H    ;after executing an interrupt,
                                ;reset SP
        MOV     P2,    #03H    ;read in the nominal location
        LCALL   SER          ;for joint 4
        MOV     REST3, A
        MOV     P2,    #03H
        LCALL   SER
        MOV     REST3, A
        MOV     P2,    #03H
        LCALL   SER
        MOV     REST3, A

        MOV     P2,    #02H    ;read in the nominal location

```

```

    LCALL SER          ;for joint 3
    MOV  REST2, A
    MOV  P2, #02H
    LCALL SER
    MOV  REST2, A
    MOV  P2, #02H
    LCALL SER
    MOV  REST2, A

    MOV  P2, #01H ;read in the nominal location
    LCALL SER ;for joint 2
    MOV  REST1, A
    MOV  P2, #01H
    LCALL SER
    MOV  REST1, A
    MOV  P2, #01H
    LCALL SER
    MOV  REST1, A

; MOV  P2, #00H ;read in the nominal location
; LCALL SER ;for joint 1
; MOV  REST0, A
; MOV  P2, #00H
; LCALL SER
; MOV  REST0, A
; MOV  P2, #00H
; LCALL SER
; MOV  REST0, A

; ** position control for joint 1 **
MAIN0: ; MOV  P2, #00H ;read in the actual location
; LCALL SER
; MOV  P2, #00H
; LCALL SER
; MOV  P2, #00H
; LCALL SER
; CLR  C
; SUBB A, REST0 ;compare nominal and actual
; JZ  MAIN1 ;location

; JNC  M0
; CPL  A
; CLR  C
; SUBB A, #04H ;precision of the position
; JNC  NEG_M0
; LJMP MAIN1

;M0: CLR  C
; SUBB A, #04H ;precision of the position
; JNC  POS_M0
; LJMP MAIN1

;POS_M0: MOV  P1, #11H ;move the joint one step up/left
; LCALL DELAY
; MOV  P1, #0FFH
; LCALL DELAY
; LJMP MAIN0

;NEG_M0: MOV  P1, #00H ;move the joint one step
; LCALL DELAY ;down/right
; MOV  P1, #0FFH
; LCALL DELAY
; LJMP MAIN0

; ** position control for joint 2 **
MAIN1: MOV  P2, #01H ;read in the actual location
    LCALL SER
    MOV  P2, #01H
    LCALL SER

```

```

MOV     P2,      #01H
LCALL  SER
CLR     C
SUBB   A,      REST1 ;compare nominal and actual
JZ     MAIN2    ;location

JNC     M1
CPL    A
CLR     C
SUBB   A,      #08H ;precision of the position
JNC    NEG_M1
LJMP   MAIN2

M1:    CLR     C
SUBB   A,      #08H ;precision of the position
JNC    POS_M1
LJMP   MAIN2

POS_M1: MOV     P1,      #33H ;move the joint one step up/left
LCALL  DELAY
MOV     P1,      #0FFH
LCALL  DELAY
LJMP   MAIN1

NEG_M1: MOV     P1,      #22H ;move the joint one step
LCALL  DELAY ;down/right
MOV     P1,      #0FFH
LCALL  DELAY
LJMP   MAIN1

; ** position control for joint 3 **
MAIN2: MOV     P2,      #02H
LCALL  SER
MOV     P2,      #02H
LCALL  SER
MOV     P2,      #02H
LCALL  SER
CLR     C
SUBB   A,      REST2
JZ     MAIN3

JNC     M2
CPL    A
CLR     C
SUBB   A,      #04H ;erlaubte Toleranz
JNC    NEG_M2
LJMP   MAIN3

M2:    CLR     C
SUBB   A,      #04H ;erlaubte Toleranz
JNC    POS_M2
LJMP   MAIN3

POS_M2: MOV     P1,      #55H
LCALL  DELAY
MOV     P1,      #0FFH
LCALL  DELAY
LJMP   MAIN2

NEG_M2: MOV     P1,      #44H
LCALL  DELAY
MOV     P1,      #0FFH
LCALL  DELAY
LJMP   MAIN2

MAIN3: MOV     P2,      #03H
LCALL  SER
MOV     P2,      #03H

```

```

        LCALL SER
        MOV P2, #03H
        LCALL SER
        CLR C
        SUBB A, REST3
        JNZ M3a
        LJMP MAIN0

M3a:    JNC M3
        CPL A
        CLR C
        SUBB A, #0FH ;erlaubte Toleranz
        JNC NEG_M3
        LJMP MAIN0

M3:     CLR C
        SUBB A, #0FH ;erlaubte Toleranz
        JNC POS_M3
        LJMP MAIN0

POS_M3: MOV P1, #77H
        LCALL DELAY
        MOV P1, #0FFH
        LCALL DELAY
        LJMP MAIN3

NEG_M3: MOV P1, #66H
        LCALL DELAY
        MOV P1, #0FFH
        LCALL DELAY
        LJMP MAIN3

;*** USER INPUT ***
;** interrupt 1 **

READ:   MOV P1, #0FFH ;switch all valves off
        PUSH PSW
        MOV P2, #0FFH
        JB P3.3, XXX ;user data available ?
        MOV A, P2 ;read user input
        CLR P2
        JMP O9
XXX:    LJMP OEND

;*** change mode ? ***
O9:     CJNE A, #09FH, O9b
        JB FLAG_K9, O9a
        SETB FLAG_K9 ;change to setup mode
O9y:    JNB P3.3, O9y
        LJMP OEND
O9a:    CLR FLAG_K9 ;return to operation mode
O9z:    JNB P3.3, O9z
        LJMP OEND
O9b:    JNB FLAG_K9, OA ;jump to execute setup mode
        LJMP S1

;*** OPERATION MODE ***

;** move the chosen joint **
OA:     CJNE A, #0AFH, O0 ;user input key A
        LCALL UP ;move arm up/left
        LJMP OEND

```

```

00:    CJNE    A,      #0FH,    01    ;user input key 0
      LCALL   DOWN
      LJMP    OEND
; ** choose a joint **
01:    CJNE    A,      #1FH,    02    ;user input key 1
      MOV     VX_1,    #00H
      MOV     VX_2,    #11H
      MOV     SPEED,  SPE_0
      LJMP    OEND
02:    CJNE    A,      #2FH,    03    ;user input key 2
      MOV     VX_1,    #22H
      MOV     VX_2,    #33H
      MOV     SPEED,  SPE_1
      LJMP    OEND
03:    CJNE    A,      #3FH,    04    ;user input key 3
      MOV     VX_1,    #44H
      MOV     VX_2,    #55H
      MOV     SPEED,  SPE_2
      LJMP    OEND
04:    CJNE    A,      #4FH,    05    ;user input key 4
      MOV     VX_1,    #66H
      MOV     VX_2,    #77H
      MOV     SPEED,  SPE_3
      LJMP    OEND
05:    CJNE    A,      #5FH,    07    ;user input key 5
      MOV     VX_1,    #88H
      MOV     VX_2,    #99H
      MOV     SPEED,  SPE_4
      LJMP    OEND
; ** move joint without PWM **
07:    CJNE    A,      #7FH,    08    ;user input key 7
      MOV     P1,     VX_2
07a:   JNB     P3.3,    07a
      MOV     P1,     #0FFH
      LJMP    OEND
08:    CJNE    A,      #8FH,    0B    ;user input key 8
      MOV     P1,     VX_1
08a:   JNB     P3.3,    08a
      MOV     P1,     #0FFH
      LJMP    OEND
; ** move the arm automatically to a nominal location **
0B:    CJNE    A,      #0BFH,    0C    ;user input key B
      LCALL   M_F1_0
      LJMP    OEND
0C:    ;LJMP    OEND
      CJNE    A,      #0CFH,    0D    ;user input key C
      LCALL   M_F2_0
      LJMP    OEND
0D:    CJNE    A,      #0DFH,    0E    ;user input key D
      LCALL   M_F3_0
      LJMP    OEND
0E:    CJNE    A,      #0EFH,    0F    ;user input key E
      LCALL   M_F4_0
      LJMP    OEND
0F:    CJNE    A,      #0FFH,    0G    ;user input key F
      LCALL   M_F5_0
0G:    LJMP    OEND
; **** SETUP MODE ****
; ** choose a speed **
S1:    CJNE    A,      #1FH,    S2
      MOV     SPE_0,  #0AH

```

```

MOV     SPE_1, #0AH
MOV     SPE_2, #0AH
MOV     SPE_3, #0AH
MOV     SPE_4, #0FH
LJMP   SEND
S2:    CJNE   A, #2FH, S3
MOV     SPE_0, #0FH
MOV     SPE_1, #0FH
MOV     SPE_2, #0FH
MOV     SPE_3, #0FH
MOV     SPE_4, #0FH
LJMP   SEND
S3:    CJNE   A, #3FH, SB
MOV     SPE_0, #60H
MOV     SPE_1, #60H
MOV     SPE_2, #60H
MOV     SPE_3, #60H
MOV     SPE_4, #60H
LJMP   SEND

; ** store a function location **
; * store function location key B *
SB:    CJNE   A, #0BFH, SC
;MOV    P2, #00H ;read in the actual location of joint 1
;LCALL  SER
;MOV    P2, #00H
;LCALL  SER
;MOV    P2, #00H
;LCALL  SER
;MOV    F1_0, A

MOV    P2, #01H ;read in the actual location of joint 2
LCALL  SER
MOV    P2, #01H
LCALL  SER
MOV    P2, #01H
LCALL  SER
MOV    F1_1, A

MOV    P2, #02H ;read in the actual location of joint 3
LCALL  SER
MOV    P2, #02H
LCALL  SER
MOV    P2, #02H
LCALL  SER
MOV    F1_2, A

MOV    P2, #03H ;read in the actual location of joint 4
LCALL  SER
MOV    P2, #03H
LCALL  SER
MOV    P2, #03H
LCALL  SER
MOV    F1_3, A
LJMP   SEND

; * store function location key C *
SC:    CJNE   A, #0CFH, SD ;
;MOV    P2, #00H ;read in the actual location of joint 1
;LCALL  SER
;MOV    P2, #00H
;LCALL  SER
;MOV    P2, #00H
;LCALL  SER
;MOV    F2_0, A

MOV    P2, #01H ;read in the actual location of joint 2
LCALL  SER

```



```

MOV     P2,     #01H
LCALL  SER
MOV     P2,     #01H
LCALL  SER
MOV     F2_1,   A

MOV     P2,     #02H      ;read in the actual location of joint 3
LCALL  SER
MOV     P2,     #02H
LCALL  SER
MOV     P2,     #02H
LCALL  SER
MOV     F2_2,   A

MOV     P2,     #03H      ;read in the actual location of joint 4
LCALL  SER
MOV     P2,     #03H
LCALL  SER
MOV     P2,     #03H
LCALL  SER
MOV     F2_3,   A
LJMP   SEND

;* store function location key D *
SD:    CJNE    A,     #0DFH, SE ;
      ;MOV     P2,     #00H      ;read in the actual location of joint 1
      ;LCALL  SER
      ;MOV     P2,     #00H
      ;LCALL  SER
      ;MOV     P2,     #00H
      ;LCALL  SER
      ;MOV     F3_0,   A

MOV     P2,     #01H      ;read in the actual location of joint 2
LCALL  SER
MOV     P2,     #01H
LCALL  SER
MOV     P2,     #01H
LCALL  SER
MOV     F3_1,   A

MOV     P2,     #02H      ;read in the actual location of joint 3
LCALL  SER
MOV     P2,     #02H
LCALL  SER
MOV     P2,     #02H
LCALL  SER
MOV     F3_2,   A

MOV     P2,     #03H      ;read in the actual location of joint 4
LCALL  SER
MOV     P2,     #03H
LCALL  SER
MOV     P2,     #03H
LCALL  SER
MOV     F3_3,   A
LJMP   SEND

;* store function location key E *
SE:    CJNE    A,     #0EFH, SF ;
      ;MOV     P2,     #00H      ;read in the actual location of joint 1
      ;LCALL  SER
      ;MOV     P2,     #00H
      ;LCALL  SER
      ;MOV     P2,     #00H
      ;LCALL  SER

```

```

;MOV      F4_0,   A
MOV       P2,    #01H      ;read in the actual location of joint 2
LCALL    SER
MOV       P2,    #01H
LCALL    SER
MOV       P2,    #01H
LCALL    SER
MOV       F4_1,   A

MOV       P2,    #02H      ;read in the actual location of joint 3
LCALL    SER
MOV       P2,    #02H
LCALL    SER
MOV       P2,    #02H
LCALL    SER
MOV       F4_2,   A

MOV       P2,    #03H      ;read in the actual location of joint 4
LCALL    SER
MOV       P2,    #03H
LCALL    SER
MOV       P2,    #03H
LCALL    SER
MOV       F4_3,   A
LJMP     SEND

;* store function location key F *
SF:      CJNE    A,    #0FFH, SEND ;
;MOV      P2,    #00H      ;read in the actual location of joint 1
;LCALL    SER
;MOV      P2,    #00H
;LCALL    SER
;MOV      P2,    #00H
;LCALL    SER
;MOV      F5_0,   A

MOV       P2,    #01H      ;read in the actual location of joint 2
LCALL    SER
MOV       P2,    #01H
LCALL    SER
MOV       P2,    #01H
LCALL    SER
MOV       F5_1,   A

MOV       P2,    #02H      ;read in the actual location of joint 3
LCALL    SER
MOV       P2,    #02H
LCALL    SER
MOV       P2,    #02H
LCALL    SER
MOV       F5_2,   A

MOV       P2,    #03H      ;read in the actual location of joint 4
LCALL    SER
MOV       P2,    #03H
LCALL    SER
MOV       P2,    #03H
LCALL    SER
MOV       F5_3,   A
LJMP     SEND

;* end of setup mode *
SEND:    CLR     FLAG_K9
SENDa:   JNB     P3.3, SENDa

;* end of user input *
OEND:    POP     PSW

```

```

    POP     B
    POP     B
    MOV     B,      #3FH
    PUSH    B
    MOV     B,      #00H
    PUSH    B
    RETI

; ** move the chosen joint right/down **
DOWN:  MOV     P1,    VX_1
        LCALL   DELAY
        MOV     P1,    #0FFH
        LCALL   DELAY2
        RET

; ** move the chosen joint left/up **
UP:    MOV     P1,    VX_2
        LCALL   DELAY
        MOV     P1,    #0FFH
        LCALL   DELAY2
        RET

; *** move the arm to function location F1 ***
; ** move joint 1 **
M_F1_0: ;MOV     P2,    #00H
        ;LCALL   SER
        ;CLR     C
        ;SUBB   A,      F1_0
        ;JZ     M_F1_1

        ;JNC    M_10
        ;CPL    A
        ;CLR     C
        ;SUBB   A,      #00H
        ;JNC    NEG1_0
        ;JMP    M_F1_1

;M_10:  CLR     C
        ;SUBB   A,      #00H
        ;JNC    POS1_0
        ;JMP    M_F1_1

;POS1_0: MOV     P1,    #11H
        ;LCALL   DELAY
        ;MOV     P1,    #0FFH
        ;LCALL   DELAY
        ;JMP    M_F1_0

;NEG1_0: MOV     P1,    #00H
        ;LCALL   DELAY
        ;MOV     P1,    #0FFH
        ;LCALL   DELAY
        ;JMP    M_F1_0

; ** move joint 2 **
M_F1_1: MOV     P2,    #01H
        LCALL   SER
        MOV     P2,    #01H
        LCALL   SER
        MOV     P2,    #01H
        LCALL   SER

        CLR     C

```

```

        SUBB    A,          F1_1
        JZ      M_F1_2

        JNC    M_11
        CPL    A
        CLR    C
        SUBB   A,          #04H
        JNC    NEG1_1
        LJMP   M_F1_2

M_11:    CLR    C
        SUBB   A,          #04H
        JNC    POS1_1
        LJMP   M_F1_2

POS1_1:  MOV    P1,        #33H
        LCALL  DELAY
        MOV    P1,        #0FFH
        LCALL  DELAY
        LJMP   M_F1_1

NEG1_1:  MOV    P1,        #22H
        LCALL  DELAY
        MOV    P1,        #0FFH
        LCALL  DELAY
        LJMP   M_F1_1

; ** move joint 3 **
M_F1_2:  MOV    P2,        #02H
        LCALL  SER
        MOV    P2,        #02H
        LCALL  SER
        MOV    P2,        #02H
        LCALL  SER
        CLR    C
        SUBB   A,          F1_2
        JZ      M_F1_3

        JNC    M_12
        CPL    A
        CLR    C
        SUBB   A,          #00H
        JNC    NEG1_2
        LJMP   M_F1_3

M_12:    CLR    C
        SUBB   A,          #00H
        JNC    POS1_2
        LJMP   M_F1_3

POS1_2:  MOV    P1,        #55H
        LCALL  DELAY
        MOV    P1,        #0FFH
        LCALL  DELAY
        JMP    M_F1_2

NEG1_2:  MOV    P1,        #44H
        LCALL  DELAY
        MOV    P1,        #0FFH
        LCALL  DELAY
        JMP    M_F1_2

; ** move joint 4 **
M_F1_3:  MOV    P2,        #03H
        LCALL  SER
        MOV    P2,        #03H
        LCALL  SER
        MOV    P2,        #03H
        LCALL  SER
        CLR    C

```

```

        SUBB    A,      F1_3
        JZ      END_F1

        JNC     M_13
        CPL     A
        CLR     C
        SUBB    A,      #04H
        JNC     NEG1_3
        LJMP   END_F1

M_13:   CLR     C
        SUBB    A,      #04H
        JNC     POS1_3
        LJMP   END_F1

POS1_3: MOV     P1,      #77H
        LCALL  DELAY
        MOV     P1,      #0FFH
        LCALL  DELAY
        JMP     M_F1_3

NEG1_3: MOV     P1,      #66H
        LCALL  DELAY
        MOV     P1,      #0FFH
        LCALL  DELAY
        JMP     M_F1_3

END_F1: RET

;*** move the arm to function location F2 ***
;** move joint 1 **
M_F2_0: ;MOV     P2,      #00H
        ;LCALL  SER
        ;CLR     C
        ;SUBB    A,      F2_0
        ;JZ      M_F2_1

        ;JNC     M_20
        ;CPL     A
        ;CLR     C
        ;SUBB    A,      #00H
        ;JNC     NEG2_0
        ;JMP     M_F2_1

;M_20:  CLR     C
        ;SUBB    A,      #00H
        ;JNC     POS2_0
        ;JMP     M_F2_1

;POS2_0: MOV     P1,      #11H
        ;LCALL  DELAY
        ;MOV     P1,      #0FFH
        ;LCALL  DELAY
        ;JMP     M_F2_0

;NEG2_0: MOV     P1,      #00H
        ;LCALL  DELAY
        ;MOV     P1,      #0FFH
        ;LCALL  DELAY
        ;JMP     M_F2_0

;** move joint 2 **
M_F2_1: MOV     P2,      #01H
        LCALL  SER
        MOV     P2,      #01H
        LCALL  SER
        MOV     P2,      #01H
        LCALL  SER

```

```

        CLR      C
        SUBB    A,      F2_1
        JZ      M_F2_2

        JNC     M_21
        CPL     A
        CLR     C
        SUBB    A,      #04H
        JNC     NEG2_1
        LJMP    M_F2_2

M_21:   CLR      C
        SUBB    A,      #04H
        JNC     POS2_1
        LJMP    M_F2_2

POS2_1: MOV      P1,      #33H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        LJMP    M_F2_1

NEG2_1: MOV      P1,      #22H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        LJMP    M_F2_1

; ** move joint 3 **
M_F2_2: MOV      P2,      #02H
        LCALL   SER
        MOV     P2,      #02H
        LCALL   SER
        MOV     P2,      #02H
        LCALL   SER
        CLR     C
        SUBB    A,      F2_2
        JZ      M_F2_3

        JNC     M_22
        CPL     A
        CLR     C
        SUBB    A,      #00H
        JNC     NEG2_2
        LJMP    M_F2_3

M_22:   CLR      C
        SUBB    A,      #00H
        JNC     POS2_2
        LJMP    M_F2_3

POS2_2: MOV      P1,      #55H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        JMP     M_F2_2

NEG2_2: MOV      P1,      #44H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        JMP     M_F2_2

; ** move joint 4 **
M_F2_3: MOV      P2,      #03H
        LCALL   SER
        MOV     P2,      #03H
        LCALL   SER
        MOV     P2,      #03H
        LCALL   SER

```

```

        CLR      C
        SUBB    A,      F2_3
        JZ      END_F2

        JNC     M_23
        CPL     A
        CLR     C
        SUBB    A,      #04H
        JNC     NEG2_3
        LJMP    END_F2

M_23:   CLR      C
        SUBB    A,      #04H
        JNC     POS2_3
        LJMP    END_F2

POS2_3: MOV      P1,      #77H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        JMP     M_F2_3

NEG2_3: MOV      P1,      #66H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        JMP     M_F2_3

END_F2: RET

;*** move the arm to function location F3 ***
; ** move joint 1 **
M_F3_0: ;MOV     P2,      #00H
        ;LCALL   SER
        ;CLR     C
        ;SUBB    A,      F3_0
        ;JZ      M_F3_1

        ;JNC     M_30
        ;CPL     A
        ;CLR     C
        ;SUBB    A,      #00H
        ;JNC     NEG3_0
        ;JMP     M_F3_1

;M_30:  CLR      C
        ;SUBB    A,      #00H
        ;JNC     POS3_0
        ;JMP     M_F3_1

;POS3_0: MOV     P1,      #11H
        ;LCALL   DELAY
        ;MOV     P1,      #0FFH
        ;LCALL   DELAY
        ;JMP     M_F3_0

;NEG3_0: MOV     P1,      #00H
        ;LCALL   DELAY
        ;MOV     P1,      #0FFH
        ;LCALL   DELAY
        ;JMP     M_F3_0

; ** move joint 2 **
M_F3_1: MOV     P2,      #01H
        LCALL   SER
        MOV     P2,      #01H
        LCALL   SER
        MOV     P2,      #01H
        LCALL   SER

```

```

        CLR      C
        SUBB    A,      F3_1
        JZ      M_F3_2

        JNC     M_31
        CPL     A
        CLR     C
        SUBB    A,      #04H
        JNC     NEG3_1
        LJMP   M_F3_2

M_31:   CLR      C
        SUBB    A,      #04H
        JNC     POS3_1
        LJMP   M_F3_2

POS3_1: MOV      P1,      #33H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        LJMP   M_F3_1

NEG3_1: MOV      P1,      #22H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        LJMP   M_F3_1

; ** move joint 3 **
M_F3_2: MOV      P2,      #02H
        LCALL   SER
        MOV     P2,      #02H
        LCALL   SER
        MOV     P2,      #02H
        LCALL   SER
        CLR     C
        SUBB    A,      F3_2
        JZ      M_F3_3

        JNC     M_32
        CPL     A
        CLR     C
        SUBB    A,      #00H
        JNC     NEG3_2
        LJMP   M_F3_3

M_32:   CLR      C
        SUBB    A,      #00H
        JNC     POS3_2
        LJMP   M_F3_3

POS3_2: MOV      P1,      #55H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        JMP     M_F3_2

NEG3_2: MOV      P1,      #44H
        LCALL   DELAY
        MOV     P1,      #0FFH
        LCALL   DELAY
        JMP     M_F3_2

; ** move joint 4 **
M_F3_3: MOV      P2,      #03H
        LCALL   SER
        MOV     P2,      #03H
        LCALL   SER
        MOV     P2,      #03H

```



```

        LCALL  SER
        CLR   C
        SUBB  A,    F3_3
        JZ    END_F3

        JNC   M_33
        CPL   A
        CLR   C
        SUBB  A,    #04H
        JNC   NEG3_3
        LJMP  END_F3
M_33:   CLR   C
        SUBB  A,    #04H
        JNC   POS3_3
        LJMP  END_F3
POS3_3: MOV   P1,    #77H
        LCALL DELAY
        MOV   P1,    #0FFH
        LCALL DELAY
        JMP   M_F3_3
NEG3_3: MOV   P1,    #66H
        LCALL DELAY
        MOV   P1,    #0FFH
        LCALL DELAY
        JMP   M_F3_3

END_F3: RET

;*** move the arm to function location F4 ***
;** move joint 1 **
M_F4_0: ;MOV   P2,    #00H
        ;LCALL SER
        ;CLR   C
        ;SUBB  A,    F4_0
        ;JZ    M_F4_1

        ;JNC   M_40
        ;CPL   A
        ;CLR   C
        ;SUBB  A,    #00H
        ;JNC   NEG4_0
        ;JMP   M_F4_1
;M_40:  CLR   C
        ;SUBB  A,    #00H
        ;JNC   POS4_0
        ;JMP   M_F4_1
;POS4_0: MOV   P1,    #11H
        ;LCALL DELAY
        ;MOV   P1,    #0FFH
        ;LCALL DELAY
        ;JMP   M_F4_0
;NEG4_0: MOV   P1,    #00H
        ;LCALL DELAY
        ;MOV   P1,    #0FFH
        ;LCALL DELAY
        ;JMP   M_F4_0

;** move joint 2 **
M_F4_1: MOV   P2,    #01H
        LCALL  SER
        MOV   P2,    #01H
        LCALL  SER
        MOV   P2,    #01H

```

```

        LCALL    SER

        CLR     C
        SUBB   A,      F4_1
        JZ     M_F4_2

        JNC    M_41
        CPL    A
        CLR    C
        SUBB   A,      #04H
        JNC    NEG4_1
        LJMP   M_F4_2

M_41:   CLR     C
        SUBB   A,      #04H
        JNC    POS4_1
        LJMP   M_F4_2

POS4_1: MOV     P1,      #33H
        LCALL  DELAY
        MOV    P1,      #0FFH
        LCALL  DELAY
        LJMP   M_F4_1

NEG4_1: MOV     P1,      #22H
        LCALL  DELAY
        MOV    P1,      #0FFH
        LCALL  DELAY
        LJMP   M_F4_1

; ** move joint 3 **
M_F4_2: MOV     P2,      #02H
        LCALL  SER
        MOV    P2,      #02H
        LCALL  SER
        MOV    P2,      #02H
        LCALL  SER
        CLR    C
        SUBB   A,      F4_2
        JZ     M_F4_3

        JNC    M_42
        CPL    A
        CLR    C
        SUBB   A,      #00H
        JNC    NEG4_2
        LJMP   M_F4_3

M_42:   CLR     C
        SUBB   A,      #00H
        JNC    POS4_2
        LJMP   M_F4_3

POS4_2: MOV     P1,      #55H
        LCALL  DELAY
        MOV    P1,      #0FFH
        LCALL  DELAY
        JMP    M_F4_2

NEG4_2: MOV     P1,      #44H
        LCALL  DELAY
        MOV    P1,      #0FFH
        LCALL  DELAY
        JMP    M_F4_2

; ** move joint 4 **
M_F4_3: MOV     P2,      #03H
        LCALL  SER
        MOV    P2,      #03H
        LCALL  SER

```

```

MOV      P2,      #03H
LCALL   SER
CLR     C
SUBB    A,      F4_3
JZ      END_F4

JNC     M_43
CPL    A
CLR     C
SUBB    A,      #04H
JNC     NEG4_3
LJMP   END_F4

M_43:   CLR     C
SUBB    A,      #04H
JNC     POS4_3
LJMP   END_F4

POS4_3: MOV     P1,      #77H
LCALL   DELAY
MOV     P1,      #0FFH
LCALL   DELAY
JMP     M_F4_3

NEG4_3: MOV     P1,      #66H
LCALL   DELAY
MOV     P1,      #0FFH
LCALL   DELAY
JMP     M_F4_3

END_F4: RET

;*** move the arm to function location F5 ***
;** move joint 1 **
M_F5_0: ;MOV     P2,      #00H
        ;LCALL   SER
        ;CLR     C
        ;SUBB    A,      F5_0
        ;JZ      M_F5_1

        ;JNC     M_50
        ;CPL    A
        ;CLR     C
        ;SUBB    A,      #00H
        ;JNC     NEG5_0
        ;JMP     M_F5_1

;M_50:  CLR     C
        ;SUBB    A,      #00H
        ;JNC     POS5_0
        ;JMP     M_F5_1

;POS5_0: MOV     P1,      #11H
        ;LCALL   DELAY
        ;MOV     P1,      #0FFH
        ;LCALL   DELAY
        ;JMP     M_F5_0

;NEG5_0: MOV     P1,      #00H
        ;LCALL   DELAY
        ;MOV     P1,      #0FFH
        ;LCALL   DELAY
        ;JMP     M_F5_0

;** move joint 2 **
M_F5_1: MOV     P2,      #01H
        LCALL   SER
        MOV     P2,      #01H
        LCALL   SER

```

```

MOV     P2,     #01H
LCALL  SER

CLR     C
SUBB   A,     F5_1
JZ     M_F5_2

JNC    M_51
CPL    A
CLR    C
SUBB   A,     #04H
JNC    NEG5_1
LJMP   M_F5_2

M_51:  CLR     C
SUBB   A,     #04H
JNC    POS5_1
LJMP   M_F5_2

POS5_1: MOV    P1,     #33H
LCALL  DELAY
MOV    P1,     #0FFH
LCALL  DELAY
LJMP   M_F5_1

NEG5_1: MOV    P1,     #22H
LCALL  DELAY
MOV    P1,     #0FFH
LCALL  DELAY
LJMP   M_F5_1

; ** move joint 3 **
M_F5_2: MOV    P2,     #02H
LCALL  SER
MOV    P2,     #02H
LCALL  SER
MOV    P2,     #02H
LCALL  SER
CLR    C
SUBB   A,     F5_2
JZ     M_F5_3

JNC    M_52
CPL    A
CLR    C
SUBB   A,     #00H
JNC    NEG5_2
LJMP   M_F5_3

M_52:  CLR     C
SUBB   A,     #00H
JNC    POS5_2
LJMP   M_F5_3

POS5_2: MOV    P1,     #55H
LCALL  DELAY
MOV    P1,     #0FFH
LCALL  DELAY
JMP    M_F5_2

NEG5_2: MOV    P1,     #44H
LCALL  DELAY
MOV    P1,     #0FFH
LCALL  DELAY
JMP    M_F5_2

; ** move joint 4 **
M_F5_3: MOV    P2,     #03H
LCALL  SER
MOV    P2,     #03H

```

```

        LCALL  SER
        MOV   P2,    #03H
        LCALL  SER
        CLR   C
        SUBB  A,     F5_3
        JZ    END_F5

        JNC   M_53
        CPL   A
        CLR   C
        SUBB  A,     #04H
        JNC  NEG5_3
        LJMP  END_F5

M_53:   CLR   C
        SUBB  A,     #04H
        JNC  POS5_3
        LJMP  END_F5

POS5_3: MOV   P1,    #77H
        LCALL  DELAY
        MOV   P1,    #0FFH
        LCALL  DELAY
        JMP   M_F5_3

NEG5_3: MOV   P1,    #66H
        LCALL  DELAY
        MOV   P1,    #0FFH
        LCALL  DELAY
        JMP   M_F5_3

END_F5: RET

;*** READ IN THE POSITION OF THE JOINT VIA THE SERIAL PORT ***
SER:   ;MOV   SCON,   #10H
        CLR   RI
        MOV   A,     SBUF
SERa:  JNB   RI,     SERa
        ;CLR   RI
        ;MOV   A,     SBUF
        MOV   P2,    #0FFH
        RLC   A           ;the digital value delivered by an
        MOV   DIG.0,  C   ;A/D-converter has to be swapped
        RLC   A           ;Bit 7 --> Bit 0
        MOV   DIG.1,  C   ;Bit 6 --> Bit 1
        RLC   A           ;Bit 5 --> Bit 2
        MOV   DIG.2,  C   ;Bit 4 --> Bit 3
        RLC   A           ;Bit 3 --> Bit 4
        MOV   DIG.3,  C   ;Bit 2 --> Bit 5
        RLC   A           ;Bit 1 --> Bit 6
        MOV   DIG.4,  C   ;Bit 0 --> Bit 7
        RLC   A
        MOV   DIG.5,  C
        RLC   A
        MOV   DIG.6,  C
        RLC   A
        MOV   DIG.7,  C
        MOV   A,     DIG   ;DIG = correct position data byte
        RET

;*** DELAY/SPEED ROUTINES ***

; ** fixed speed for position control and automatic movement **
DELAY: MOV   R6,     #10H
DEL1:  MOV   R7,     #0AFH
DEL2:  DJNZ  R7,     DEL2

```

```
        DJNZ  R6,    DEL1
        RET

; ** variable speed for manual movement of the arm **
DELAY2: MOV    R6,    SPEED
DEL21:  MOV    R7,    #0FFH
DEL22:  DJNZ  R7,    DEL22
        DJNZ  R6,    DEL21
        RET

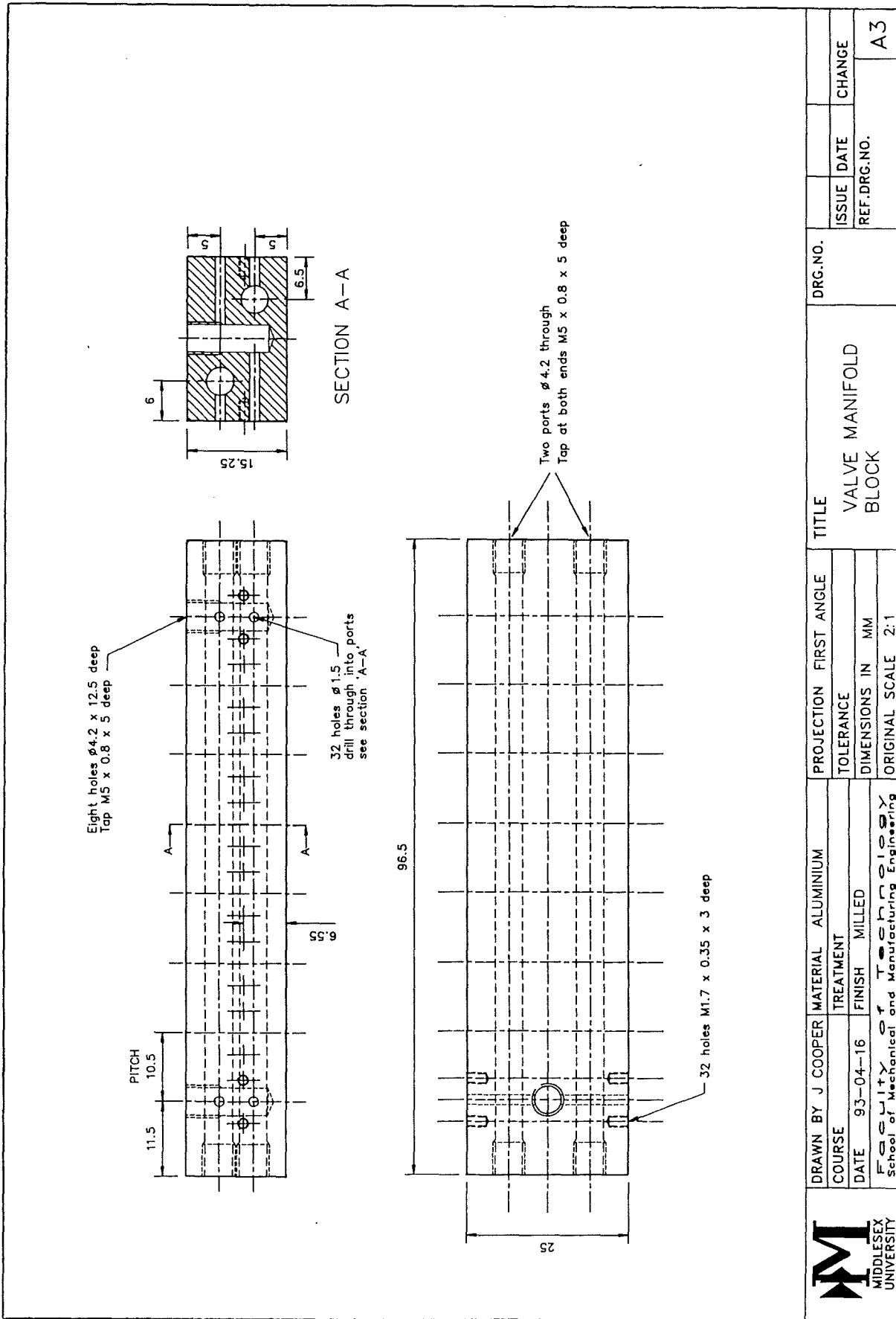
SCH:    SJMP  SCH


END
```



**APPENDIX Q : WORKING DRAWING OF THE MAIN MANIFOLD BLOCK**

---



|   |  |                    |                        |                      |         |             |      |        |
|---|--|--------------------|------------------------|----------------------|---------|-------------|------|--------|
| <br>MIDDLESEX UNIVERSITY | DRAWN BY J COOPER                                  | MATERIAL ALUMINIUM | PROJECTION FIRST ANGLE | TITLE                | DRG.NO. | ISSUE       | DATE | CHANGE |
|   | COURSE TREATMENT                                   | FINISH MILLED      | TOLERANCE              | VALVE MANIFOLD BLOCK |         | REF.DRG.NO. |      |        |
| DATE 93-04-16   | SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING | DIMENSIONS IN MM   | ORIGINAL SCALE 2:1     |                      |         |             |      | A3     |





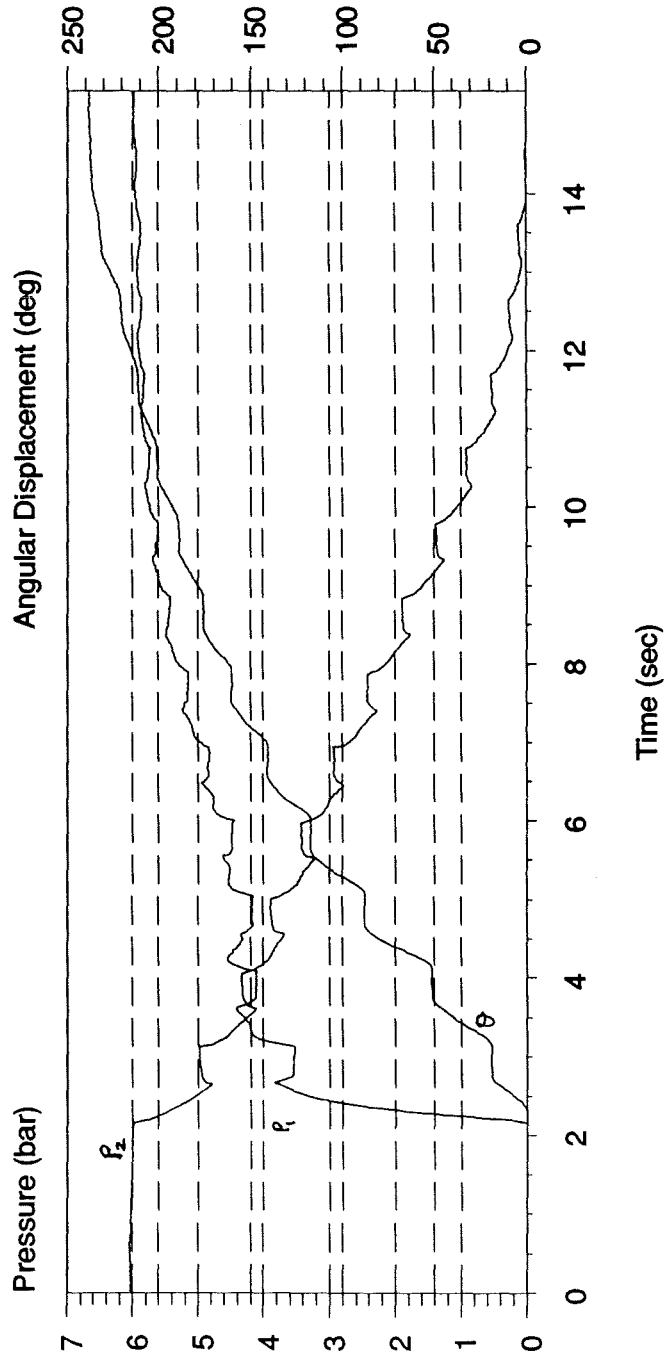
**APPENDIX R : EFFECT OF PWM FREQUENCY ON ACTUATOR STROKE**

---

# Dynamic Performance of Dual Muscle Actuator

Muscle Type: 60 x 90 ; 5

Muscle 1 Pressurizing, Muscle 2 Venting



23/11/92

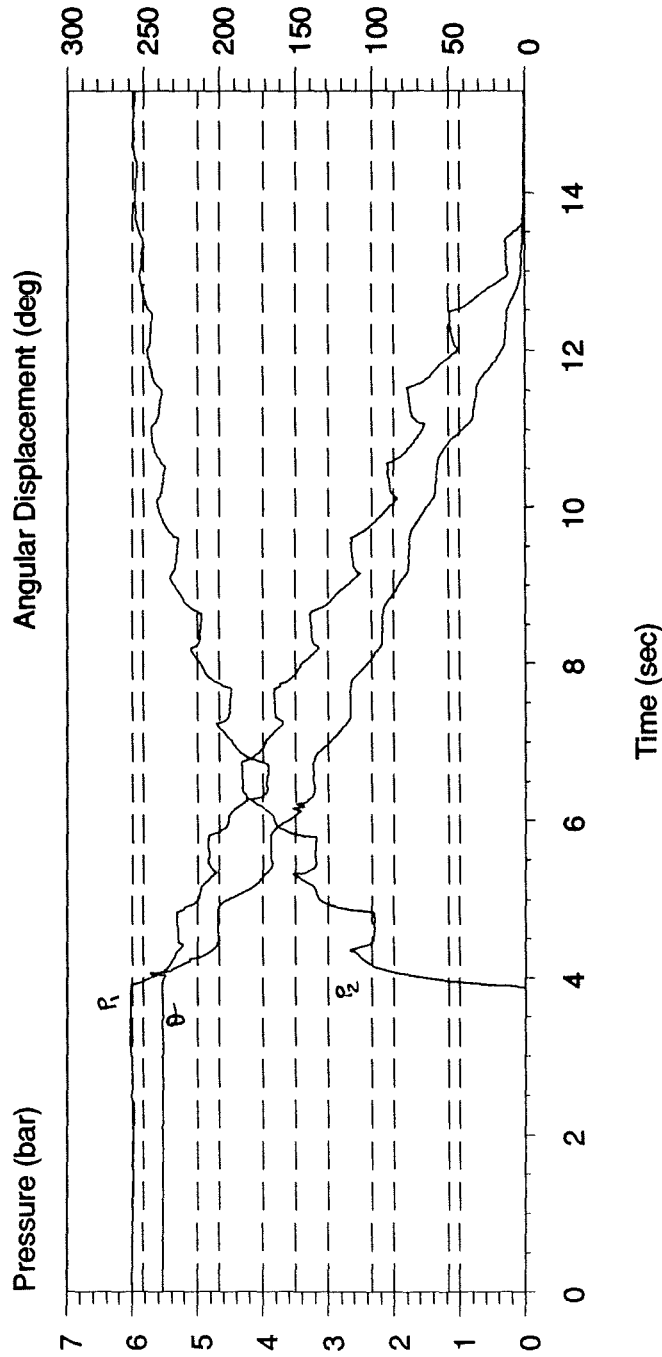
PWM frequency = 1 Hz; Muscle 1 opposing torque load

Reservoir fitted 0.5 l; Torque Load = 2.328 Nm

# Dynamic Performance of Dual Flexator Actuator

Muscle Type: 60 x 90 ; 5

Muscle 1 Venting, Muscle 2 Pressurizing



23/11/92

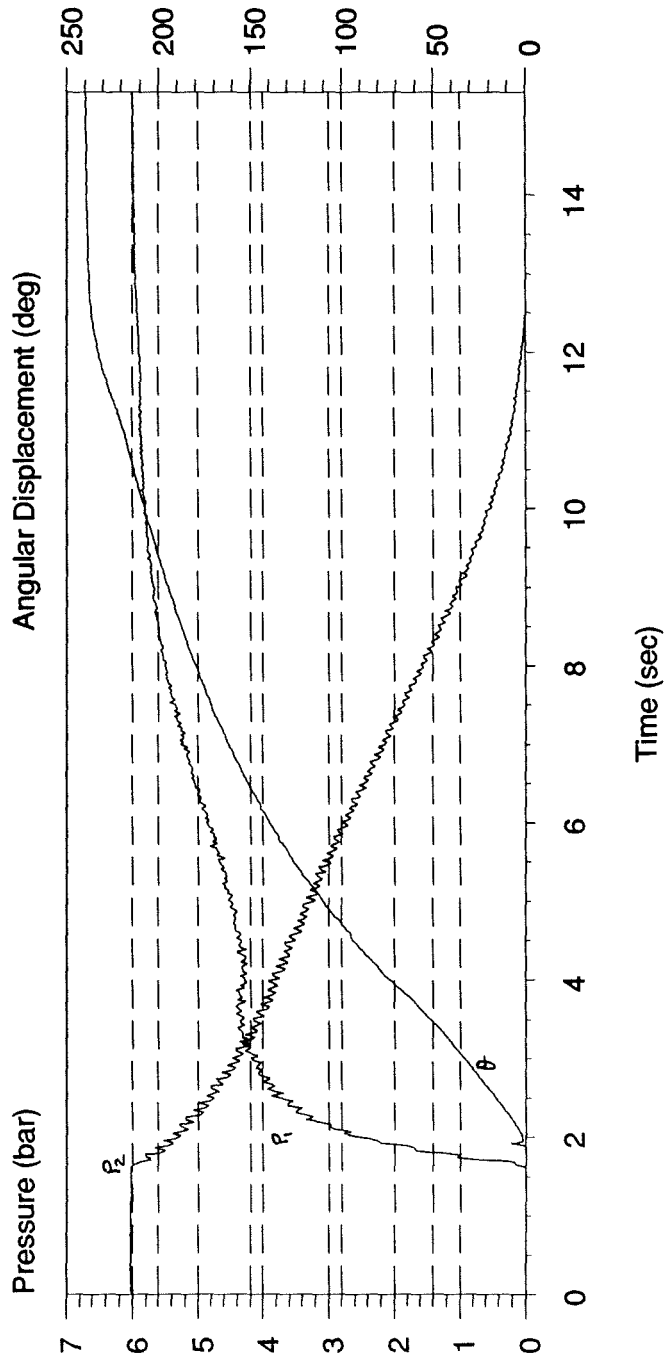
PWM frequency = 1 Hz; Muscle 1 opposing torque load

Reservoir fitted 0.5 l; Torque Load = 2.328 Nm

# Dynamic Performance of Dual Muscle Actuator

Muscle Type: 60 x 90 ; 5

Muscle 1 Pressurizing, Muscle 2 Venting



23/11/92

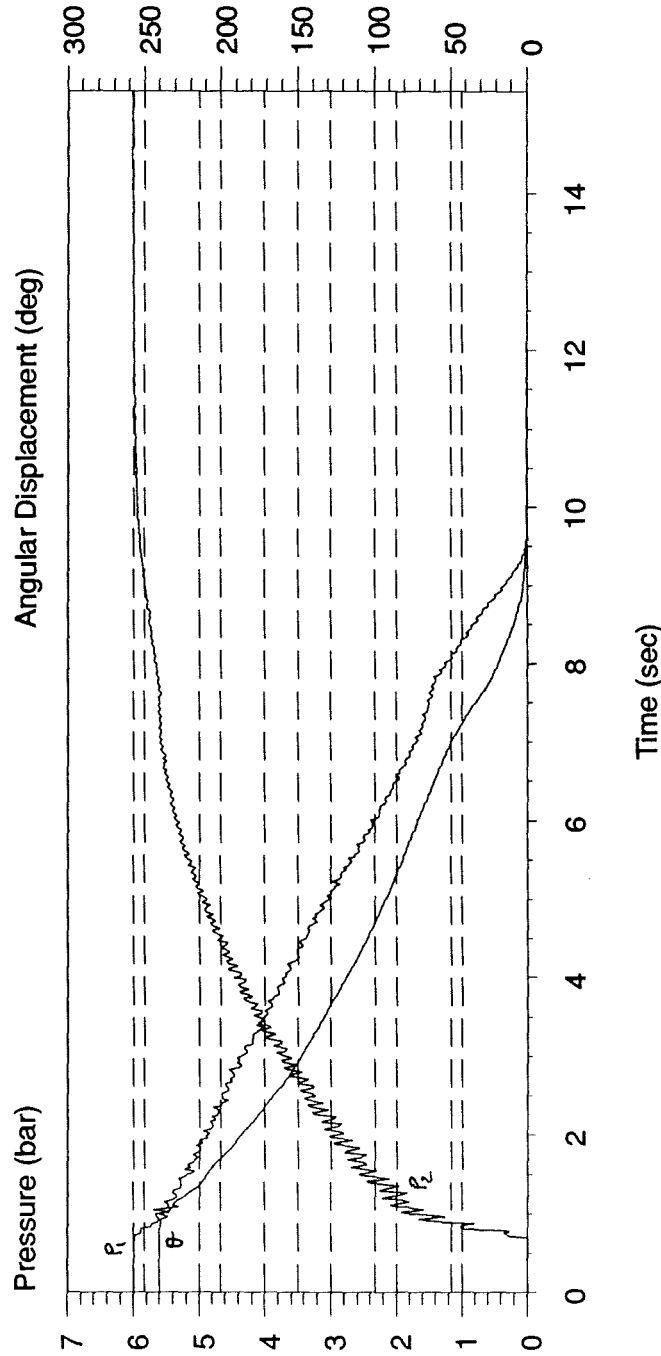
PWM frequency = 10 Hz; Muscle 1 opposing torque load

Reservoir fitted 0.5 l; Torque Load = 2.328 Nm

# Dynamic Performance of Dual Muscle Actuator

Muscle Type: 60 x 90 ; 5

Muscle 1 Venting, Muscle 2 Pressurizing



23/11/92

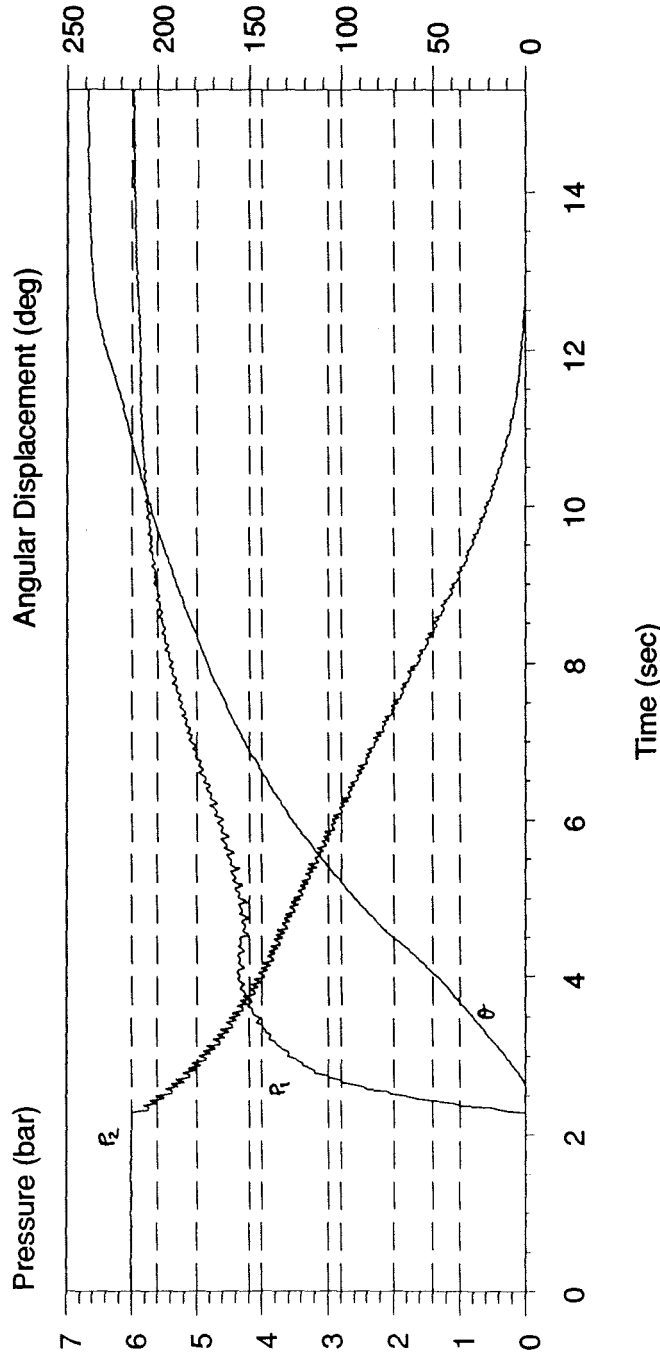
PWM frequency = 10 Hz; Muscle 1 opposing torque load

Reservoir fitted 0.5 l; Torque Load = 2.328 Nm

# Dynamic Performance of Dual Muscle Actuator

Muscle Type: 60 x 90 ; 5

Muscle 1 Pressurizing, Muscle 2 Venting



23/11/92

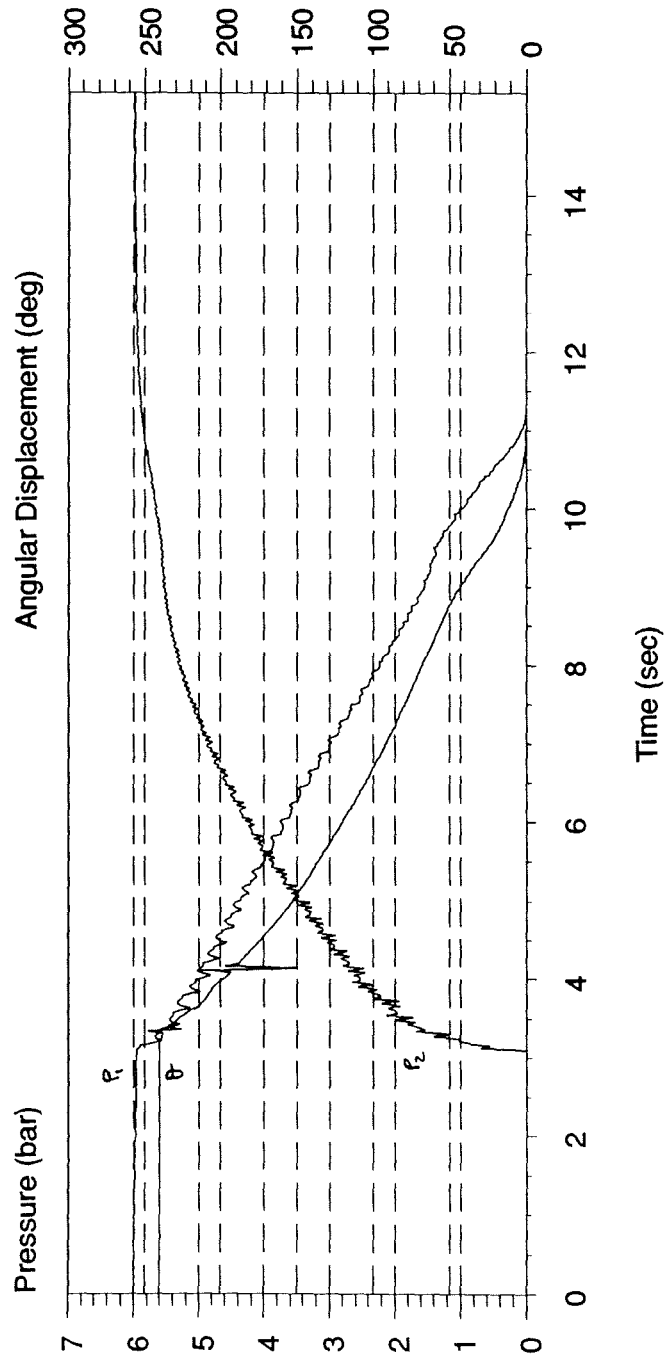
PWM frequency = 20 Hz; Muscle 1 opposing torque load

Reservoir fitted 0.5 l; Torque Load = 2.328 Nm

# Dynamic Performance of Dual Muscle Actuator

Muscle Type: 60 x 90 ; 5

Muscle 1 Venting, Muscle 2 Pressurizing



23/11/92

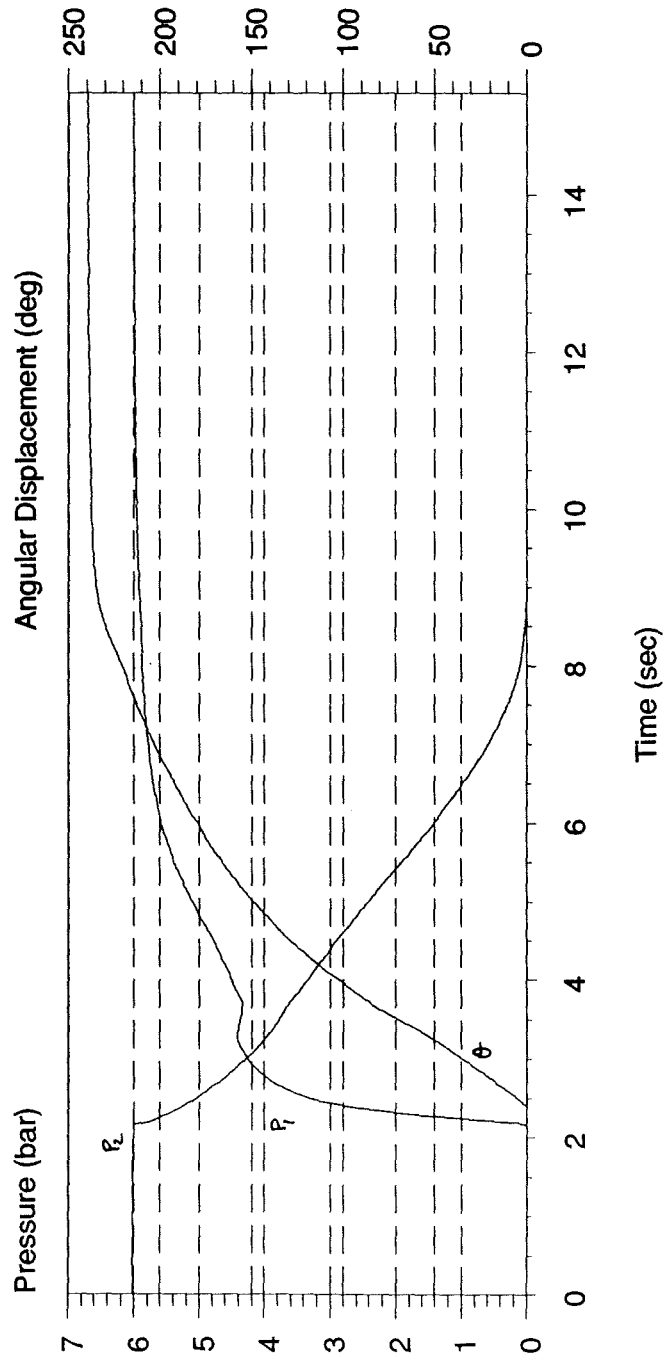
PWM frequency = 20 Hz; Muscle 1 opposing torque load

Reservoir fitted 0.5 l; Torque Load = 2.328 Nm

# Dynamic Performance of Dual Muscle Actuator

Muscle Type: 60 x 90 ; 5

Muscle 1 Pressurizing, Muscle 2 Venting



23/11/92

No PWM; Muscle 1 opposing torque load

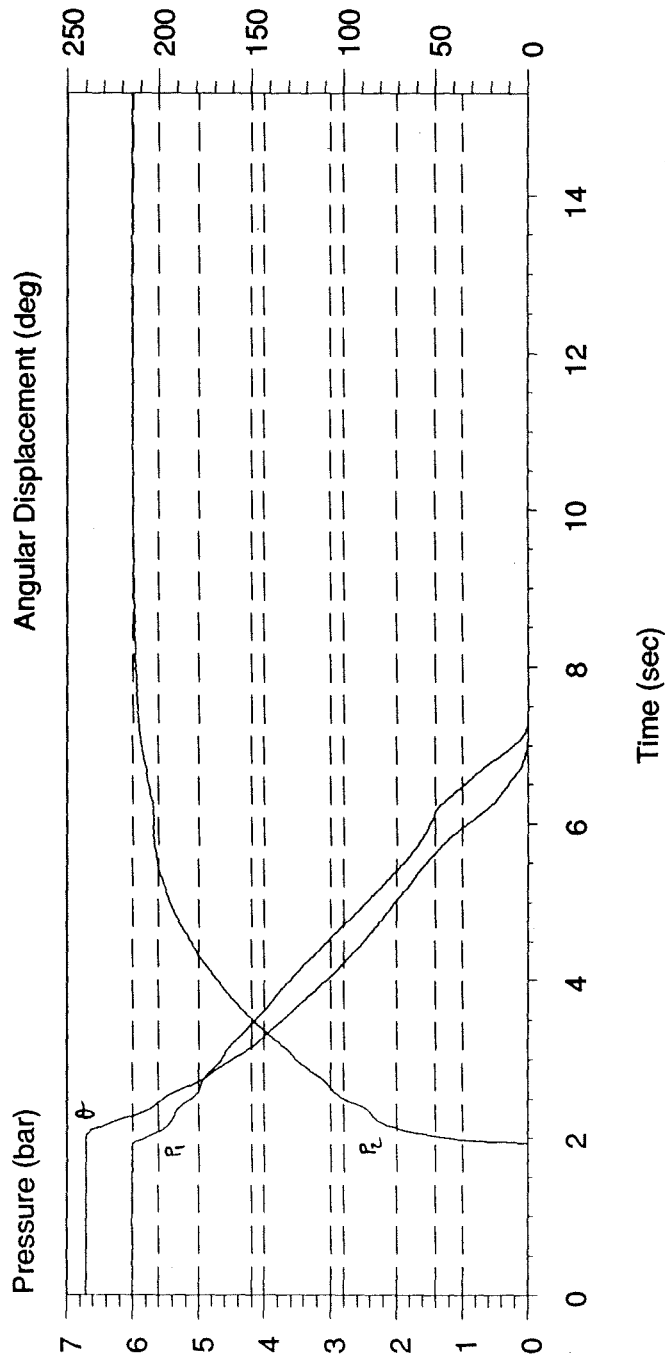
Reservoir fitted 0.5 l; Torque Load = 2.328 Nm



# Dynamic Performance of Dual Muscle Actuator

Muscle Type: 60 x 90 ; 5

Muscle 1 Venting, Muscle 2 Pressurizing



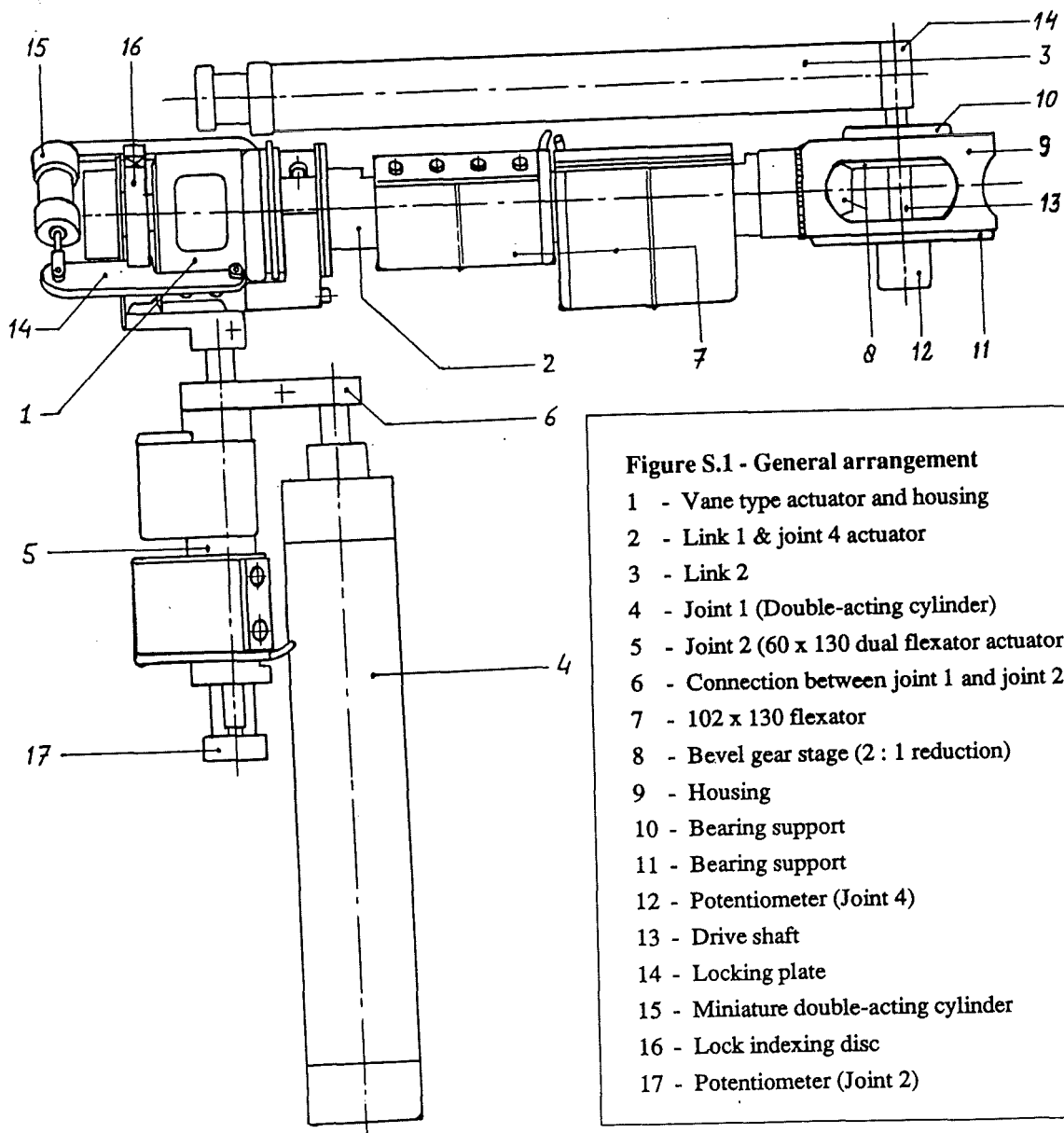
23/11/92

No PWM; Muscle 1 opposing torque load

Reservoir fitted 0.5 l; Torque Load = 2.328 Nm



**APPENDIX S : SECOND PROTOTYPE DESIGNS**



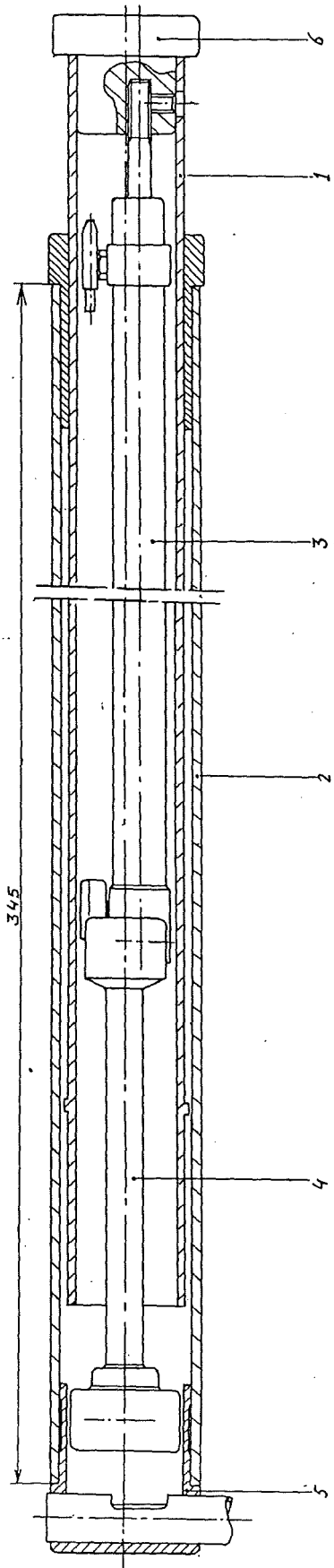


Figure S.2 - Sectional drawing of link 2

- 1 - Inner tube (Aluminium)
- 2 - Outer tube (Carbon fibre)
- 3 - Double-acting cylinder (160 mm stroke)
- 4 - Extension and cylinder connector
- 5 - Link 2 connector
- 6 - Wrist // End effector mounting point

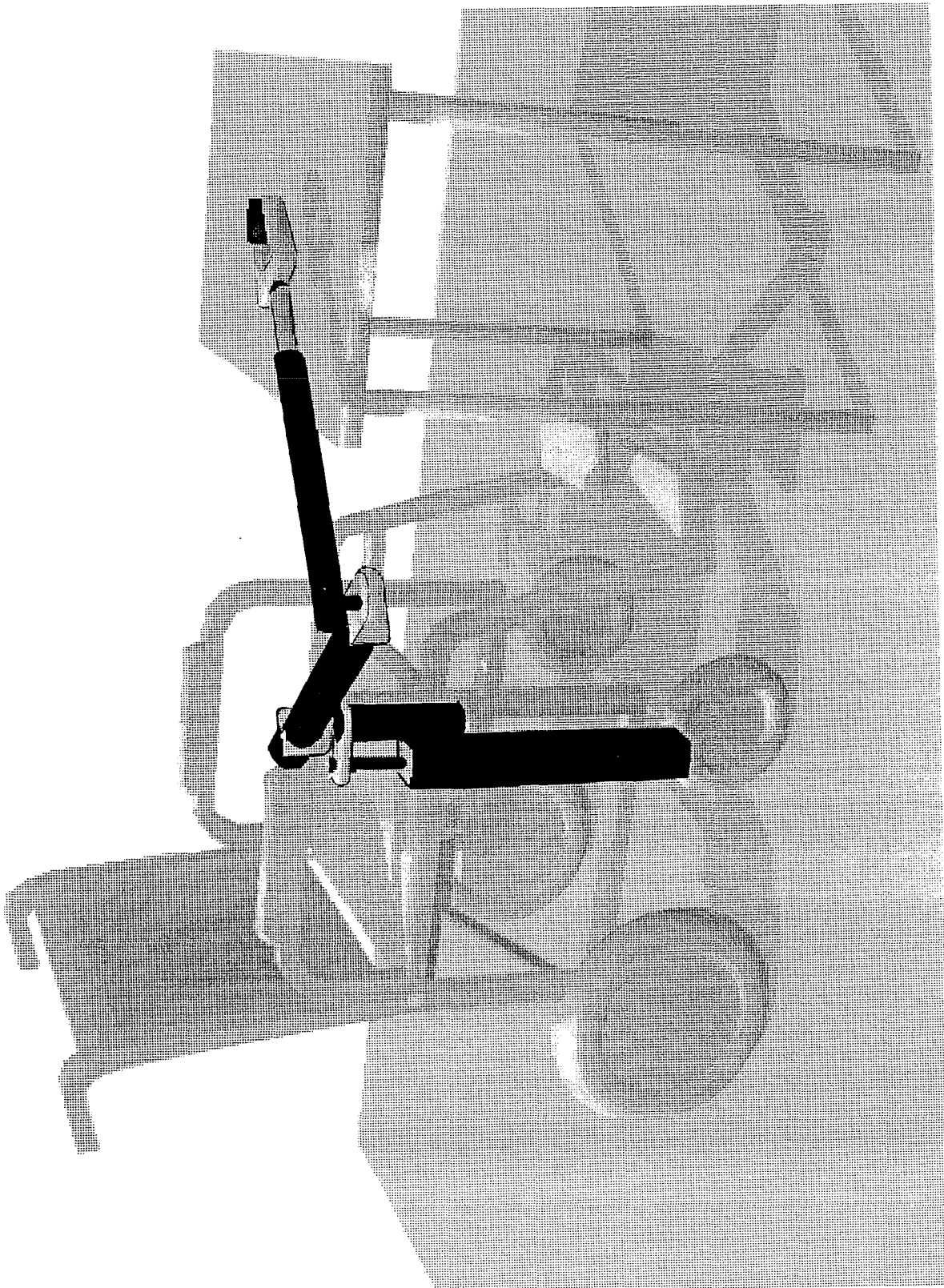


Figure S.3 - Conceptual model of prototype II

## *Published Work*

---

- [1] **Prior, S.D., White, A.S., Gill, R., Parsons, J.T. and Warner, P.R.** : "A novel pneumatic actuator.", *IEEE/SMC '93 Conference on Systems Engineering in the Service of Humans*. Le Touquet, France, October 17-20 1993. (in press).
- [2] **Prior, S.D. and Warner, P.R.** : "Wheelchair-mounted robots for the home environment.", *IEEE/RSJ International Conference on Intelligent Robots and Systems '93*, Yokohama, Japan, July 26-30 1993.
- [3] **Prior, S.D., Warner, P.R., Parsons, J.T. and Oettinger, P.** : "Design and development of an electric wheelchair mounted robotic arm for use by people with physical disabilities.", *Transaction on Advanced Technologies in Robotics, Mechatronics & Manufacturing Systems*, IMACS, Elsevier, July 1993.<sup>1</sup>
- [4] **Prior, S.D., Warner, P.R., White, A.S., Parsons, J.T. and Gill, R.** : "Actuators for rehabilitation robots.", *Mechatronics - Special Issue on Robot Actuators*, Vol. 3, No. 3, pp.285-294, June 1993.
- [5] **Prior, S.D., Warner, P.R., Parsons, J.T. and Oettinger, P.** : "Design and development of an electric wheelchair mounted robotic arm for use by people with physical disabilities.", *International Symposium on Robotics, Mechatronics and Manufacturing Systems '92 Kobe*, Japan, pp.541-546, Sept. 16-20 1992.
- [6] **Prior, S.D., Warner, P.R., Parsons, J.T., White, A.S., and Oettinger, P.** : "A hybrid rehabilitation robotic arm for the physically disabled electric wheelchair user.", *Proceedings of the 1992 International Conference on Rehabilitation Robotics*, Keele University, Sept. 15-16 1992.
- [7] **Prior, S.D. & Warner, P.R.** : "The flexator as a robotic actuator.", *IEE Colloquium on Robot Actuators*, Digest No: 1991/146, Oct 7 1991.
- [8] **Prior, S.D.** : "Computer aided design of rehabilitation robots.", *Proceedings of the 6<sup>th</sup> International Conference on CAD/CAM, Robotics and Factories of the Future*, London, pp.14-19, August 19-22 1991.
- [9] **Prior, S.D. & Warner, P.R.** : "Low-cost pneumatic actuators for applications in rehabilitation robotics.", *14<sup>th</sup> Annual RESNA Conference*, Kansas City, Missouri, pp.19-20, June 21-26 1991.
- [10] **Prior S.D. & Warner, P.R.** : "A New development in low-cost pneumatic actuators", *Proceedings of the 5<sup>th</sup> International Conference on Advanced Robotics*, Pisa, Italy, June 19-22 1991, Vol. 2, pp.1590-1593.
- [11] **Prior, S.D., Warner, P.R., Platts, R.G.S., Wright, K.W.J., White, A.S., Parsons, J.T.** : "Low-cost pneumatic actuators for use in rehabilitation robotic applications.", *Proceedings of the 1991 International Conference on Rehabilitation Robotics*, Atlanta, Georgia, pp.39-53, June 19-20 1991.

1 Reference [3] is identical to reference [5].

- [12] **Prior, S.D.** : "An electric wheelchair mounted robotic arm - A survey of potential users.", *The Journal of Medical Engineering & Technology*, Vol. 14, No. 4, pp.143-154, July/August 1990.
- [13] **Prior, S.D.** : "A survey of potential users of an electric wheelchair mounted robotic arm.", *Proceedings of the 13<sup>th</sup> Annual RESNA Conference*, pp.297-298, Washington D.C., June 15-20 1990.
- [14] **Prior, S.D. & Warner, P.R.** : "A review of world rehabilitation robotics research.", *IEE Colloquium on High-Tech Help for the Handicapped*, Digest No. 1990/054, 2 April 1990.