

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Design and Motion Control of a 6-UPS Fully Parallel Robot for Long Bone Fracture Reduction

A thesis presented in partial fulfillment of the requirements for the degree of

Master of Engineering

In Mechatronics

at Massey University Albany, New Zealand.

Yimin Wu

2007

ACKNOWLEDGEMENTS

I would like to thank those who have helped me throughout the project. I would firstly like to thank my wife, Mei and also my mother, RongXiang for looking after my newborn daughter, ChuQi. Without their help I could not have concentrated on the project. I would like to thank Professor Peter Xu and Dr Johan Potgieter who are my project supervisors. The project could not have been completed without their advice and guidance.

To the following engineering staff members, Dr Olaf Diegel, Gordon Warren, Eddy Rogers and Raymond Hoffmann, I would like to express my gratitude for all their time spent in making the heavy robot framework and giving me lots of suggestions in mechanical design.

I would also like to thank my friends, BiQing Chen, Steven, and all other postgraduates for the happy time shared during the project and the chance to exchange strange and wonderful ideas.

Last, but not least, I would like to thank my lovely princess, ChuQi, for all the joy she has brought to my life. I would like to dedicate the thesis to her.

ABSTRACT

The incidences of long bone fractures in New Zealand are approximately 1 in 10,000. Long bones such as tibia and femur have complicated anatomic structures, making the realignment of these long bone fractures reliant on the skill of the surgeon. The drawbacks of current practice result in long time exposure to radiation, slow recovery and possible morbidity. A semi-automated long bone fracture reduction system based on a 6-DOF parallel robot platform has been in development since 2004.

The developed 6-DOF parallel robot platform comprises of six linear actuators with rotary incremental encoders. To implement a realignment of long bone fractures, a framework for the 6-DOF platform robot has been developed. The inverse kinematics and singularity of the 6-DOF parallel robot has been studied to obtain the actions and Jacobin matrices.

In motion control a multiple axis motion controller and amplifiers were used for 6-DOF parallel robot. PID tuning algorithms were developed based on the combination of the general tuning result and the contour control principle. The PID parameters have been validated by a numbers of experiments.

The practical realignment of bone fractures requires a "Pull-Rotate-Push" action implemented by the 6-DOF parallel robot. After calibration, the reduction trajectories were generated accurately. The actual trials on the artificial fractures have shown that the robot developed is capable of performing the required reduction motion.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	III
ABSTRACT	IV
TABLE OF CONTENTS	V
LIST OF FIGURES	VIII
LIST OF TABLES	XI
Chapter 1 Introduction	1
1.1 Introduction	1
1.1.1 Definition	1
1.1.2 System structure	1
1.1.3 Project aim	3
1.2. Background	3
1.2.1 The current bone realignment procedure	3
1.2.2 Contribution by preceding students	5
1.2.3 Objectives	5
Chapter 2 Literature review	7
2.1 Overview of parallel robots	7
2.1.1 Parallel robots: definition	7
2.1.2 Parallel robot vs. serial robot	8
2.2 Architectures	10
2.2.1 Notation of parallel robots	10
2.2.2 6-DOF manipulators	10
2.2.3 6-UPS robot (Gough-Stewart platform)	10
2.3 Existing applications of 6-UPS robot	11
2.3.1 Spatial application	11
2.3.2 Vibration	12
2.3.3 Medical application	13
Chapter 3 Analysis and design of the parallel robot	14
3.1 Introduction	14
3.2 Analysis of the 6-UPS robot	14
3.2.1 Coordinate system assignment	14

3.2.2 Inverse kinematics	16
3.2.3 Singularity	18
3.3 Framework design	23
3.3.1 Current operating framework	23
3.3.2 Design concept	24
3.3.3 Implementation and assembly	27
3.4 Performance analysis.	30
3.4.1 Workspace	30
3.4.2 Height adjustment	31
3.5 Conclusion	31
Chapter 4 Motion control for the 6-UPS parallel robot	
4.1 Introduction	
4.2 Motion control architecture	
4.2.1 Controller architecture	
4.2.2 Motion system architecture	
4.3 Motion system elements	35
4.3.1 Motor (actuator)	35
4.3.2 Amplifier (Driver)	37
4.3.3 Switching power supply	
4.3.4 DMC-1800 motion control card	
4.3.5 Encoder	40
4.4 Motion control mode	46
4.4.1 Overview of control mode	46
4.4.2 Selection of control mode	
4.4.3 Independent Axis Positioning (IAP)	
4.4.4 Contour mode	
4.5 PID Tuning	51
4.5.1 Methodology	51
4.5.2 Mathematical modeling	
4.5.3 Automatic tuning in WSDK	
4.5.4 Consideration and solution	
4.5.5 Verification of PID parameters	61
4.6. Conclusion	
Chapter 5 Operation and performance evaluation	67
5.1 Practical surgical operation	67
5.2 Calibration	68
5.2.1 Initialized configuration	69
5.2.2 Procedure of calibration	70

5.3 Generated trajectories and implementation	73
5.3.1 Trajectories generation	73
5.3.2 Implementation on the robot	78
5.4 Existing problems	80
5.4.1 Representation of problems	80
5.4.2 Possible reasons	80
5.4.3 Analysis and solution	81
Chapter 6 Conclusion and future developments	
6.1 Conclusion	
6.2 Future developments	
6.2.1 Encoder	
6.2.2 Spherical joint	90
6.2.3 Other suggestions	91
References	92
Appendix A	96
Appendix B	
Appendix C	105

LIST of FIGURES

Figure 1.1 Overview of the proposed system structure
Figure 1.2 Long bone fracture realignment operation
Figure 1.3 Traction machine and operation
Figure 2.1 Structures of fully parallel platform (Bruyninckx 2005)
Figure 2.2 General structure of Gough Stewart platform (Harib and Srinivasan 2003)11
Figure 2.3 A telescope pointing system (APEX assembly 2003) 12
Figure 2.4 A vibration damping (Micromega Dynamics) 12
Figure 2.5 Mini bone-attached robotic systems (Lisien et.al. 2004) 13
Figure 3.1 Z-Y-X Euler system 15
Figure 3.2 Translational Z-Y-X Euler system
Figure 3.3 Vecotrial structure for inverse kinematics
Figure 3.4 Current operating table for surgery
Figure 3.5 SolidWorks model of robot framework
Figure 3.6 Design of the 2-DOF main linkages and the attachment
Figure 3.7 Jockey stander and jockey wheel
Figure 3.8 Mobile table
Figure 3.9 Production of framework
Figure 3.10 Manikin and the fixed sciatic joint
Figure 3.11 Assembled robot with framework 29
Figure 3.12 Workspace for framework (Top View) 30
Figure 3.13 6-UPS Parallel Robot Workspace 31
Figure 4.1 DMC-1700/1800 controllers Architecture (Galil 2005) 34
Figure 4.2 Architecture Motion control system (Galil 2005)
Figure 4.3 Dimension and back fixture for LA22

Figure 4.4 Speed vs. load and current vs. load
Figure 4.5 SP-750-24 static characteristics (Mean Well 2005)
Figure 4.6 Single-ended and differential Quadrature signals (Cyber Research 2007)
Figure 4.7: Hall Effect encoder
Figure 4.8 Position sensor circuit and 3141 Hall-Effect sensor
Figure 4.9 Two transitional positions generate undesired "00 state
Figure 4.10 View of Cross section of shaft
Figure 4.11 Improved position sensor
Figure 4.12 Velocity profile in trapezoidal and triangular (Galil 2005) 49
Figure 4.13 Trajectory in contour mode (Gaili 2005) 51
Figure 4.14 System modeling for single actuator
Figure 4.15 Amplifier and motor in System modeling (Galil 2005)
Figure 4.16 Actuator control diagram
Figure 4.17 Combinable weights for PID testing
Figure 4.18 Auto Cross Frequency tuning
Figure 4.19 General tuning with 1kg of load 57
Figure 4.20: Curve follower with 1kg of load 58
Figure 4.21 Point to Point tuning with 1kg of load 59
Figure 4.22: Tuning result and step response
Figure 4.23 Four configurations of actuator in 3D space
Figure 4.24 Three testing trajectories
Figure 4.25 Result shown in WSDK
Figure 5.1 "Pull-Rotate-Push" action
Figure 5.2 Dimension of base plate and top plate
Figure 5.3 Initialized configurations for calibration and motion 70
Figure 5.4 Calibration procedure
Figure 5.5: Calculation from 30mm displacement along Z axis
Figure 5.6 Simulation and measurement
Figure 5.7 Simulation parameters setting

Figure 5.8 Create linear displacement and generated trajectory 75
Figure 5.9 α = -30 rotation
Figure 5.10 Response of a "Pull-Rotate-Push" action
Figure 5.11 Robot system and demonstration
Figure 5.12: Optimized control curve with "Cog-cog"
Figure 5.13 Damaged spherical joint
Figure 5.14 Force analyses for spherical joints
Figure 6.1 QD145 optical encoder (QPhase 2006)& ST38/50 series encoders (ServoTek 2006)
Figure 6.2: Spherical rolling joint supplied by Seiko (Hephaist Seiko 2005)

LIST of TABLES

Table 3.1: Coordinates of vertexes in the frame A and frame B 17
Table 3.2 Parts details
Table 3.3: Physical properties of EN 9 carbon steel
Table 3.4 Components of the system
Table 4.1 Specifications of Power supply 38
Table 4.1 15-Pins definition 46
Table 4.2 Control modes
Table 4.3: Properties of PID parameters (Michigan 1997)
Table 4.4: PID testing and verification
Table 5.1: Comparison of actual robot vs. theoretical model
Table 5.2 Translational displacements
Table 5.3: Edited Trajectory
Table 5.4: Rotary displacement in $\alpha = -30$ rotation
Table 5.5 Displacement for rotation
Table 5.6 Stress on the spherical joints in two placements
Table 6.1 Requirements of encoder
Table 6.2 Specifications of encoders 90

Chapter 1 Introduction

1.1 Introduction

1.1.1 Definition

A long bone fracture realignment medical robot system is under development at Massey University in Auckland. This robot system is expected to be a semi-automated fracture reduction system interacting with a Human-Machine (HM) interface. After planning and simulation through HMI in an offline mode, the repositioning movements planned by the surgeon will be performed on a robot platform whose end-effector is attached to the patient's foot. With the aid of this system, an actual manipulation of the fracture fragments will become more accurate, safe and more efficient compared with current manual procedures. The old system relies on the surgeon's experience and ability to interpret X-rays, a higher volume of X-ray exposure rate on the patients, higher risk possibility of other infections, human fatigue and lengthy operations.

1.1.2 System structure

The fracture realignment procedures consist of a planning phase (or teaching) and an operational phase. According to these two phases, the entire system has been developed as shown in Figure 1.1 (Graham et. al., 2005).



Figure 1.1 Overview of the proposed system structure

To achieve the required robot system, the following functional modules should be developed.

System modeling & software engineering is the primary module, which integrates the other subsystems for signal inputting, motion analysis, trajectory generation, motion implementation, feedback and emergency procedures.

X-ray Image processing for geometric model of fractures is to take advantage of existing digital fluoroscopic images to reconstruct fractures in a three-dimensional environment. An effective procedure is required to reduce fluoroscopic images taken, and the format of the relative displacement of fractures needs to be represented in homogenous transformations.

Motion implementation emphasizes that a compact/portable 6-DOF (Degree-Of-Freedom) parallel robot is used to provide spatial mobility for fracture reduction. The frame of robot, formation, kinematics and dynamics analysis are required to manipulate the fractures realignment in a controlled fashion.

Human machine interface for surgeons differs from an engineer's requirements. A software environment is required to be developed for surgical procedures, in which the geometric fractures can be modeled from X-ray images, and the fractures' biomechanics and robotic dynamics can be visualized, simulated and animated. A graphical user interface (GUI) for the surgeon's convenience of planning and decision making is essential.

1.1.3 Project aim

This thesis is concerned with the motion implementation of a standardized 6-DOF parallel robot for the use in the surgical environment. In 2004, a 6-DOF parallel Stewart-Gough platform was introduced into this project. This Stewart Gough platform comprises of six linear actuators attached between a top and base plate. The ends of each linear actuator are equipped with a 3-DOF joint and a 2-DOF joint. In principle, the linear extension and retraction of the six actuators gives the platform six degrees-of-freedom positioning capabilities, consisting of three translational and three rotational degree-of-freedoms (Harib and Srinivasan, 2003).

This platform was constructed and single motor was tested. As a platform, it was not working in a control fashion. The trial and evaluation of the prototype system did not begin in a real operation theatre environment, the robot framework in term of real environment was missing and the analysis of the kinematics and performance was not completed. All these issues are required to be studied deeply before the platform would get into a working system. In view of this, this project was aimed to work out the solution for these issues clearly and provide more valuable experiences and sources for the future system integration.

1.2. Background

1.2.1 The current bone realignment procedure

The initial requirements of the robot were specified by a surgeon, who hoped Massey University to develop a robot system for image-guided orthopedic surgery. The surgical procedure is described as below.

3

The patient's foot is attached to a traction machine connected to the patient's table through a 2-DOF linkage. The traction machine is able to slide along one of links to adjust linear displacement according to patient leg length and has the purpose of pulling the broken bone fragments into partial alignment. This is the main method of realigning during the operation (Figure 1.2).



Figure 1.2 Long bone fracture realignment operation

The alignment of the broken bones is viewed in real time using a fluoroscope that is the large cylindrical instrument with a low power portable x-ray machine that can take short burst images that provide a video display of the position of the broken bone fragments to surgeons during the operation. Using resource provided by fluoroscope, the surgeon manipulates the broken bones manually to achieve the best possible realignment. The feedback is acted on manually by the surgical assistants to align the bone parts back into the best possible alignment. Once aligned, the surgeon pins the bones into position and the operation is complete. After the operation the patient's leg is placed in a cast. The traction machine has a rack and pinion mechanism that provides the axial force to pull the leg. The foot is attached to the foot holster and the traction machine assembly is rigidly attached to the operating table (Figure 1.3).



Figure 1.3 Traction machine and operation

1.2.2 Contribution by preceding students

In the past three years, a number of undergraduates have contributed to the project to various extents. Swanson (Swanson 2004) designed in SolidWorks model and built 6-DOF parallel robot. Torrance (Torrance 2004) developed a motion control system and tried on single actuator closed loop control. Ashish (Ashsih 2005) built a Hall-effect position sensor for the actuators.

1.2.3 Objectives

In early 2006, it was expected that the robot prototype should perform facture alignment procedures in a controlled fashion in the real environment and the performance of platform would be evaluated after experimentation.

To this end, objectives were identified as follows,

- Investigation and improvement of the existing design
- Design and building of a physical framework where the robot is attached
- Interfacing sensors to the motion controller
- PID tuning with effective load for all six actuators

- Trajectory generation and implementation by the robot within predefined error limitations
- Platform demonstration and simulation
- Performance evaluation and analysis
- Trouble shooting and future improvement