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PERCEPTION AND ORIENTATION ISSUES IN HUMAN CONTROL OF ROBOT MOTION

by

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for the degree of Doctor of Philosophy, May, 1991

ABSTRACT

The use of remote teach controls for programming industrial robots has led to concern over programmer safety and reliability. The primary issue is the close proximity to the robot arm required for the programmer or maintainer to clearly see the tool actions, and it is feared that errors in robot control could result in injury. The further concern that variations in teach control design could cause "negative transfer" of learning has led to a call for standardisation of robot teach controls. However, at present there is insufficient data to provide suitable design recommendations. This is because previous researchers have measured control performance on very general, and completely different, programming tasks.

This work set out to examine the motion control task, from which a framework was developed to represent the robot motion control process. This showed the decisions and actions required to achieve robot movement, together with the factors which may influence them.

Two types of influencing factors were identified: robot system factors and human cognitive factors. Robot system factors add complexity to the control task by producing motion reversals which alter the control-robot motion relationship. These motion reversals were identified during the experimental programme which examined observers' perception of robot motion under different conditions of human-robot orientation and robot arm-configuration. These determine the orientation of the robot with respect to the observer at any given time.

It was found that changes in orientation may influence the observer's perception of robot movement producing inconsistent descriptions of the same movement viewed under different orientations. Furthermore, due to the strong association between perceived movement and control selection demonstrated in these experiments, no particular differences in error performance using different control designs were observed.

It is concluded that human cognitive factors, specifically the operators' perception of robot movement and their ability to recognise motion reversals, have greater influence on control selection errors than control design per se.

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CHAPTER 1 - INTRODUCTION

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1.1 Background

Since robots were first introduced into industry in 1961, there has been rapid, if inconsistent, growth in their number (IFR, 1989). In 1988 it was estimated that there were over 280,000 industrial robots in operation worldwide (BRA,1989) and even this figure is conservative by Japanese standards since it includes only those machines defined as robots by the Robotics Industries Association (RIA), USA (ANSI, 1986). According to the RIA, a robot must be reprogrammable and multifunctional whereas the Japanese definition includes non-programmable, fixed-sequence devices and automated guided vehicles (AGV's) (JISHA,1985). Because of the confusion arising from these different definitions the International Federation of Robotics (IFR) is now proposing standardisation in robot definition and data collection (Rook, 1990). The growth in robot numbers reflects widespread applications in all aspects of manufacturing partly due to their cost-effectiveness; the economic advantages of replacing manual labour with robotics have been demonstrated in improved product quality, increased productivity and reduced costs (Foulkes and Hirsch, 1984). This has led to fears by the labour force that they will face unemployment and wage reductions as they compete with this increasingly developing technology (SME, 1985). Pro-roboticists argue, however, that the workforce will be displaced rather than replaced, and point out that robots have brought about improvements to working conditions in industry by taking over hazardous and monotonous tasks (Engelberger, 1980). On the basis of an extensive study carried out in the USA in 1985, it was predicted that 80% of workers whose jobs were taken over by robots will be relocated within the same companies and that the robot manufacturing industry itself would create more than 44,500 jobs by 1995 (SME, 1985).

Within industry, new jobs are created by the introduction of robots in programming, maintenance and supervisory tasks (Kafrissen and Stephens, 1984; Morgan, 1984). Programming involves providing the control instructions required for a robot to perform its intended task (Jablonowski and Posey, 1985), including defining the path of motion between locations as well as the functions to be carried out. Maintenance includes tool setting, fault diagnosis and calibration of the robot and its associated equipment. Supervisory tasks include monitoring of the robot whilst in its operation and ancilliary tasks such as loading and unloading workpieces from the robot and cleaning of tools etc (M. Gray, 1984). These jobs require new skills of the workforce and critics argue that they may be forced to undertake jobs to which they are ill-suited (Salvendy, 1985), and that consequently, they may find these jobs worse than those which the robot replaced (Schraft and Nicolaisen, 1986). Ironically, one of the main criticisms is that these human-robot interactions present new and unexpected hazards in the form of collision with, or trapping by, the highly flexible robot arm (see Bonney et al, 1985; Lee, 1985; Nagamachi, 1986; Percival, 1984). Although there are very few accidents reported, some fatalities have occurred (Nagamachi, 1986; NIOSH, 1984) and this has led to the image of robots as undesirable "monsters" intent on causing human injury (see Figure 2.2). In truth, however, the cause of robot-related accidents is usually found to be ineffective safeguards or 'human error' (Jiang and Gainer, 1987).

As little data is available on robot-related accidents, the research reported here has concentrated on reliability in performance which in turn may benefit safety within human-robot interaction. In particular, the interactions involved in teach control programming have been selected for examination. This was partly because this type of interaction is unique in that it can necessitate or be enhanced by close proximity to the moving robot arm, and thus can constitute a distinct hazard which cannot easily be safeguarded (Parsons, 1988). The other reason was that the author's interest in robotics stemmed from a previous study of the design of instruction manuals for robot programming (Gray, 1986). This enabled the author to gain limited experience of the programming task. Observation of the difficulties experienced in achieving correct movement of the robot arm channelled research interest into the examination of performance reliability in robot motion control.

Robot motion control is the element of teach control programming in which the robot arm is physically moved between locations; there are several reasons why reliability in motion control is desirable. First, constant correction of control motion will increase programming time which may extend robot down-time. Second, the need to perform this task at close range to the robot arm could put the programmer in danger if control errors are made (Parsons, 1988). Third, control errors resulting in robot collision could cause costly damage to the robot or other equipment.

Researchers interested in robot teach control have associated poor performance reliability in robot motion control with variations in teach pendant design (Cousins, 1988; Levosinski, 1984; Parsons and Mavor, 1986; Parsons, 1988). This may cause 'negative transfer' effects in learning whereby experience in using one control design adversely affects ability to use a different control design (Edwards, 1984; Helander and Karwan, 1988). In response to these concerns there has been a call for standardisation in teach pendant design with the aim of promoting "Uniformity, effectiveness, simplicity, efficiency, reliability and safety of operations" (Cousins, 1988 p. 429). Unfortunately current guidelines for robot teach pendants offer no specific recommendations for the most suitable design of motion controls (see for example ANSI/RIA, 1988 'Proposed standard of human engineering design criteria for hand held control pendants' and HS/G 43, 1989 'Guidelines for industrial robot safety' sections 38-50 teach pendant design). Instead, they provide general requirements for unambiguous direction labelling and the compatibility of control actuation with its corresponding robot movement in accordance with user expectations. Surprisingly little research has been carried out to experimentally evaluate motion control design and what little there is has provided insufficient and sometimes contradictory data (Brantmark et al, 1982; Creed, 1987; Ghosh and Lemay, 1985; Podgorski and Boleslawski, 1990; Rahimi and Azevedo, 1990). This is most likely due to differences in their experimental design and analysis techniques and as such their results offer no route to coherent recommendations for motion control design.

Whilst the issue of teach pendant design variation is undoubtedly important for performance reliability, it has been observed both during experimental evaluation (Creed, 1987; Ghosh and Lemay, 1985) and on-site (M.Gray, 1984) that programmers sometimes make errors because they are confused by unexpected reversals in the relationship between control movement and robot motion. British guidelines suggest that such reversals are produced by changes in human-robot orientation which adds to the complexity of the task beyond that of adjusting to different control designs and recommend that "The operator must know where to stand in relation to the robot in order to obtain the correct control orientation" (HS/G 43, 1989 para. 50). Indeed, in his experiment Creed (1987) showed that control performance was most reliable when the operator was positioned in front of the robot. Moreover, at other orientations performance reliability was influenced differently by the control design used. Unfortunately, whilst the HS/G recommendation offers a solution to this particular finding, it is not generally practicable that robot control programming should be confined to a single operator position as this would defeat the object of the remote control facility. Furthermore, the observations of Ghosh and Lemay (1985) suggest that motion reversals are not simply the result of changes in human-robot orientation but may also be produced by certain configurations of the robot arm. However, neither they nor other researchers have examined this issue in more detail and yet it would seem that this data would provide important information for control design recommendations.

1.2 Research aims

The research work so far carried out relevant to robot teach pendant design and usability has been somewhat superficial. Several studies have described the physical variations between different designs and yet no-one has questioned whether or not alternative control designs share the same functions. This has important implications for the feasibility of standardisation. The first aim of this research was to address this issue, specifically to examine the task of robot motion control using alternative teach control designs and to determine how similar their functions are.

The experimental assessments of control usability previously reported are far too general, encompassing numerous variables within the control task. As such their results are difficult to collate or even to compare, and are therefore of little use for design guidelines. Part of the reason for this is that the control task is influenced by many factors which have not been considered in previous research. These factors, such as human-robot orientation and robot arm-configuration give, rise to motion reversals which may not be anticipated by the operator. The second aim of this research was to explore these factors in detail and to determine the conditions of motion reversal.

If, as stated in the British guidelines (HS/G 43, 1989), such factors add complexity to the control task, it would be expected that control performance would be less accurate under conditions of motion reversal. The third aim of the study was to experimentally evaluate control performance under such conditions, and to compare the effect of alternative control designs on performance of the robot motion control task.

It was hoped that the results of this work might lead to a thorough understanding of the factors which influence performance reliability, from which suitable recommendations for control design could be made.

In summary then, the aims of the research reported here were to:

1. Fully explore the task of robot-motion-control using a teach pendant.
2. Identify factors which may influence performance reliability in such a task.
3. Assess the effects of these factors on performance using different teach pendants.

1.3 Organisation of thesis

This thesis is divided into eight chapters. In chapter 2 a literature review is presented which has been split into two main sections. First, a general review of industrial robots, their applications and safety issues is presented. This is followed by a detailed review of teach pendants and of the research work carried out in this area from which the research objectives are derived. Chapter 3 outlines the principles of robot motion control, thus a description of robot types, modes of programming and types of motion is given. Also a detailed description of two teach pendant designs is presented to demonstrate how teach pendants are used to achieve robot movement and the consequences of design variations for control selection. In chapter 4 the robot motion control task is examined with particular reference to the sequence of decisions and actions that are required. Consideration of the human operator as information processor led to the development of a framework of the control task which illustrates how the factors of interest may influence performance reliability. Chapter 5 outlines the experimental methodology and a full description of the experimental equipment is given. In chapter 6 all the experimental work is presented, together with the results and discussion of each of its stages. A discussion of the experimental findings and their implications for the control task and teach pendant usability is given in chapter 7. Finally, chapter 8 presents the conclusions of this research and suggestions for further work.

CHAPTER 2 - LITERATURE REVIEW

CHAPTER 2 - LITERATURE REVIEW

2.0 Introduction

It is apparent that there is a need to examine safety and performance reliability issues in robot teach control programming; therefore it is convenient to divide the literature review chapter into two main sections. For background information, the first section provides a general review of industrial robotics, their impact and applications and the safety issues which arise. The second section then examines the robot teach control process and research work carried out in this area.

2.1 Robots in Industry

2.1.1 Definition

The first industrial robot was developed by George Devol and promoted by Joseph Engelberger who founded Unimation Inc. (USA) in 1961. The robot was patented as a reprogrammable manipulator and was designed to perform "simple but heavy and distasteful tasks in industry" (Engelberger, 1985, p.3). Since then, the term "robot" has taken on many connotations from being any automated machine to the more 'humanoid' mechanical beings portrayed in science fiction novels (Asimov, 1967).

The definition of an industrial robot that is most universally accepted today is that developed by the Robotics Industries Association, USA . A robot is defined as "... a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialised devices through various programmed motions for the performance of a variety of tasks" (ANSI, 1986, p.6).

The Japanese, however, provide a different definition. Theirs encompasses a much wider range of machinery which includes non-programmable machines such as fixed-sequence devices and manual manipulators such as automated guided vehicles (AGVs) which are not regarded as robots according to the ANSI definition (JISHA, 1985). This has produced a degree of debate and contention, particularly where comparisons of robot numbers in use are concerned (Yamashita, 1985). For this reason the International Federation of Robotics (IFR) is currently intending to standardise robot definitions as well as data collection methods (Rook, 1990).

Taking the ANSI definition as standard, a robot can be distinguished from other automated systems and traditional machinery on two main aspects;

(i) It is reprogrammable which means that it is not dedicated to a single task but is able to perform many different tasks. For example, where product models may change frequently, as in the automotive industry, it is generally less costly to reprogram a robot than to rework or purchase additional hard automation (Korein and Ish-Shalom, 1987).

(ii) It is flexible in its range and type of movement which allows a wide range of applications such as spray painting, assembly, materials handling etc.

2.1.2 Why use robots?

The first application of an industrial robot was the loading and unloading of material from a die casting machine in a General Motors Plant in 1961. Meyer (1985) states that many of the early robot applications took place in such areas, where a high degree of hazard or discomfort to humans existed; examples being materials handling, foundry operations or welding. Here the benefits were immediately apparent. They could relieve the human operator of hazardous tasks where posture problems (e.g. lifting and handling tasks) and exposure to harmful substances or conditions occur such as when working with poisonous fumes, molten metal or UV radiation (Parsons, 1985).

Today, however, the decision to introduce robotics to an industrial process is based as much on the economic advantages, resulting from improved quality, increased productivity and reduced costs, as on the removal of human labour from hazardous or unpleasant work (Foulkes and Hirsch, 1984). In fact, the economic criteria can sometimes far outweigh any other for introducing robot technology into the workplace (Engelberger, 1980).

2.1.3 Robot numbers

By far the largest user of industrial robots is Japan, currently holding 68% of the world population with 176,000 robots (IFR, 1989). This figure only includes machines defined as robots according to the ANSI definition whereas numbers quoted in Japanese publications are considerably higher. For example, one set of figures published by the Japanese Industrial Robot Association (JIRA) in 1985 claimed that 206,000 robots were in use in Japan (Rook, 1987). According to the IFR figures, however, this number has not yet been reached (Rook, 1990). The next largest single country user is the USA holding a 13% share (32,000 robots), whilst European countries account for the remaining 19% (48,207 robots). Table 2.1 shows the number of industrial robots in use for each of the main user countries in the years 1981 and 1988. Prior to 1981 there were no coherent figures published. During this seven year period, there has been an approximate seven-fold increase in the world population of industrial robots, although the rate of increase has not been constant. Between 1982 and 1985 the rate of increase was approximately 42% but this fell dramatically in 1986 to 25% and was even lower in subsequent years.

It can be seen from Table 2.1 that the UK is a relatively small user of industrial robots with only 2% (5,034) of the world population. This figure falls far short of the predicted 12,500 by 1990, according to a Department of Industry survey carried out in 1980 (Ingersoll, 1980). This is because the rate of increase in the UK has been much lower than the average expected value of 30% per year (Engelberger, 1980), at about 17% per year since 1987. According to the press, this has been due to investment cutbacks and the removal of Government subsidies (Guardian, 1986).

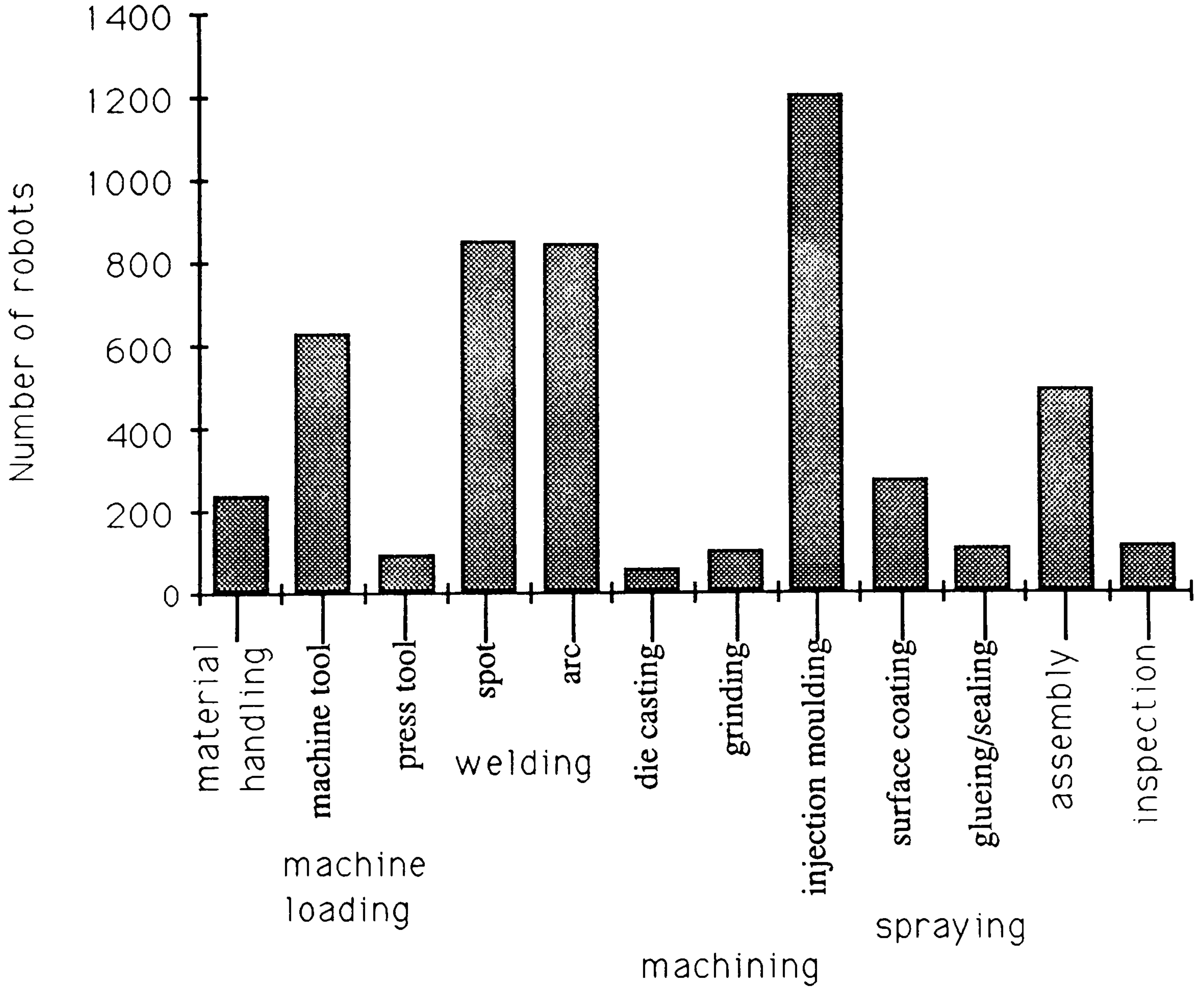
The distribution of robots in UK industry applications is shown in Figure 2.1. It can be

Table 2.1 Number of industrial robots in use worldwide in 1981 and 1988

User country	1981	1988
Japan*	21,000	176,000
USA	6,000	32,000
W. Germany	2,300	17,700
Italy	450	8,300
France	790	8,026
UK	713	5,034
Sweden	1,125	3,042
Total**	32,746	256,807

* only includes ANSI definition of robots
** includes other countries
Source: IFR (1989)

Figure 2.1 Number of robots used for a range of applications in UK industry (1989)



Source: BRA (1989)

seen that the largest area of application is welding and the largest single application is injection moulding. Moreover, robots in other applications appear to be very much fewer in number. This trend is in contrast with other EEC countries which have a more even spread of robot applications. However, it is forecast that the injection of foreign investment into UK industries and the increase of overseas-control of automotive plants in the UK, by companies who are keen users of advanced automation, could alter these trends and boost robot application in the UK (Rook, 1990).

2.1.4 Applications

The economic benefits that robots offer has led to their introduction to many types of industrial applications, some of which have already been mentioned. These are usually grouped into seven categories as follows; material handling, machine loading and unloading, welding, machining, spraying, assembly and inspection (Groover and Zimmers, 1984; Meyer, 1985). Table 2.2 shows some typical examples of industrial applications of robots in each category (adapted from Meyer, 1985, p.809) and Table 2.3 indicates the primary benefits achieved for robotising each category (also from Meyer, 1985, p.810).

Material handling

For many industries this application has been considered to be the primary function of a robot. It utilises the basic capability of transporting objects from one location to another (i.e. 'pick-and-place' tasks). The objects carried may be of a variety of sizes and weights ranging from small gear components to car body panels. White and Apple (1985) state that in 1983 more than 50% of the robots installed in the United States were performing material handling tasks. Examples of robot material handling tasks include; transfer of parts from one conveyor to another, transfer of parts from a processing line to a conveyor, or palletising parts and loading.

Table 2.2 Examples of industrial robot applications

Manufacturing operation	Robot applications
Material handling	- moving parts from warehouse to machines
	- stacking engine parts
	- transfer of auto parts from machine to overhead conveyor
	- bottle loading
	- transfer of glass from rack to cutting line
Machine loading/unloading	- loading auto parts for grinding
	- loading auto components into test machines
	- loading gears into CNC lathes
	- loading hot form presses
	- loading a punch press
	- loading die cast machine
Spray painting	- painting of aircraft parts on automated line
	- painting of underside of agricultural equipment
	- application of prime coat to truck cabs
	- application of thermal material to rockets
	- painting of appliance components
Welding	- spot welding of auto bodies
	- braze alloying of aircraft seams
	- arc welding of tractor front weight supports
	- arc welding of auto axles
Machining	- drilling aluminium panels on aircraft
	- metal flash removal from castings
	- sanding missile wings
Assembly	- assembly of aircraft parts
	- drilling and fastening metal panels
	- assembling appliance switches
	- inserting and fastening screws
Inspection	- inspecting dimensions on parts
	- inspection of hole diameter and wall thickness

Adapted from: Meyer (1985)

Table 2.3 Benefits of using robots for industrial applications

Application	Primary benefits				Robot capabilities		
	improved product quality	increased productivity	reduced costs	elimination of hazardous/ unpleasant work	transport	manipulation	sensing
Material handling			*	*	*		
Machine loading		*	*		*	*	
Spraying	*		*	*		*	
Welding		*	*	*		*	
Machining		*	*			*	
Assembly		*	*			*	*
Inspection	*						*

Adapted from: Meyer (1985)

Machine loading and unloading

This application is more sophisticated than material handling whereby robots can be used to grasp a component from a conveyor, lift it to a machine, orientate it and then insert it in the correct place for machining or for another process (Meyer, 1985). The robot works directly with the processing equipment which may be die casting, automatic press, etc. as shown in Table 2.2.

Spraying

The use of robots for paint spraying applications has supplied possibly the most tangible evidence of the benefits of their use. A major benefit has been the reduction of human exposure to toxic substances which has in turn led to reduced costs by reducing the need for elaborate and expensive ventilation systems (Groover and Zimmers, 1984). Another important cost saving has been demonstrated in the reduction of material wastage. In a direct comparison between manual spray and robotic spray, Bublick (1985) found 15-20% material saving using the robot. This saving is achieved by the robot's ability to produce a consistent coating, unlike the variations in overspray produced manually. Thus, a further benefit of the robotic spray is an improved quality in the consistency of the finish.

Welding

By far the largest application of industrial robots is in welding, and in particular spot welding, the largest user of which is the automobile industry (Jones et al, 1985). The major benefit of using robots for spot welding is that they provide a highly consistent weld quality for a wide range of manufacturing applications (Newell, 1989). Robots have also been used for arc welding although problems of accurate seam tracking have hindered their widespread use in this process. The problem is due to variations in part dimensions between different batches (e.g. distorted components). A manual welder can easily recognise such problems and can accommodate for them whereas sensor technologies are not yet sufficient to allow the robot to adjust accurately enough (TI Cox, 1987). However, if component variation is not a problem, the use of a robot for arc welding can be successful in offering benefits of up to 20%

increased productivity (Kallevig, 1985) and improved safety by removing human welders from this extremely hazardous process (Parsons, 1985).

Machining

A machining operation may be carried out by a robot either by the robot holding a tool and bringing it to contact a stationary workpiece, or the robot holding the workpiece and bringing it to contact a tool held in a fixed position. Robots are well suited to applications such as cutting or drilling particularly in the aerospace industry because of the extremely close tolerance requirements and repeatability of the task (Dreyfoos and Stragevsky, 1985). This type of work is tedious for human labour and can result in a slowing down of work rate and less accurate drilling as the worker fatigues.

However, the use of robots for other machining processes has not been widespread because of the need to extensively use jigs and fixtures for accurate positioning. This can make the process costly.

Assembly

Assembly operations are seen as an area with large potential for robot applications (Jablonowski, 1981). This is because robots potentially offer the dexterity of a human assembly operator as well as the speed and efficiency of dedicated automation assembly systems (Csakvary, 1985). The programmability of an industrial robot makes it the ideal choice for batch-type assembly operations where the products for assembly are frequently changed according to consumer demand (Smith and Nitzan, 1985).

Inspection

Traditionally, inspection has been a very labour-intensive activity which is tedious and time-consuming. For this reason, it was usually performed on a sampling basis rather than 100% inspection. Developments in sensor technology such as camera vision, lasers and ultrasonics have initiated the use of automated inspection systems operating on a 100% inspection basis. The role of robots in this process is that they can be used to guide the appropriate sensor over the workpiece. The major advantage of automated inspection is an increase in quality assurance of the distributed product. Not only because all of the products are inspected, but also because the acceptable standard criteria will be consistent and reliable whereas humans are prone to be subjective and inconsistent in their judgement (Kirsch and Kirsch, 1985).

2.1.5 The human aspect

There is no doubt that one of the principal benefits of introducing robotics to industry is cost reduction; increased product quality will result in less material wastage and high output rates can make the payback period of a robot quite short. However, there is a third reason for introducing robotics which has the direct effect of reducing costs; the replacement of manual workers at a time when labour costs have continued to escalate has provided 50-75% savings in direct labour costs for some industries (Meyer, 1985). In 1981, the Chairman of General Motors stated that, "Every time the cost of labor goes up $1 an hour, 1,000 more robots become economical" (Foulkes and Hirsch, 1984, p.95).

It would seem, therefore, that the future for workers in these traditional roles is limited. In an extensive study of the effects of robotisation, carried out in the USA in 1985, a common feeling among the labour force was that, "As robots become increasingly inexpensive, adaptable and commonplace, many jobs will be irretrievably lost and workers will suffer real losses in income as they attempt to hold on to what jobs are left". The view of management, on the other hand, was that," only low-skill, dangerous and monotonous jobs [would] be taken over by robots" and furthermore, that with retraining, "virtually all displaced workers [would] end up with more satisfying and rewarding employment" (SME, 1985, p.63).

On this issue, the consensus of opinion seems to be in favour of robotics with claims that, "Robotics will contribute importantly to the material well-being of mankind, without painful dislocation of individual workers" (Engelberger, 1980, p.116). The SME survey predicts that by 1995, there may be up to 20% of the workforce in some industries displaced by robots, but only 5-6% of these will be made unemployed. The rest will be relocated within the same companies and, of those unemployed, 93% are expected to find new jobs within one year. The robot manufacturing industry itself is expected to create more than 44,500 jobs by 1995 (SME, 1985).

So what happens to those workers whose jobs are altered by robotisation? Social scientists report various effects such as loss of skill (Salvendy, 1983), social isolation (Katzman, 1983) and reduced motivation leading to an increase in stress and absenteeism especially where robotisation causes a change in work activities which are incompatible with the workers' abilities (Argote et al, 1983). Whilst not the focus of this research, job displacement, de-skilling versus re-skilling, and alienation effects of robotisation may have some influence upon aspects of human-robot interaction in operation.

2.1.6 Human-robot interaction

The introduction of robotics into industry also creates new jobs; people are needed for programming and maintenance of the robot and its associated equipment and there will usually be a need for some kind of machine operation which may only involve monitoring of the robots' performance or may require working alongside the robot (Engelberger, 1980; Kafrissen and Stephens, 1984; Morgan, 1984). Each of these jobs involves different types of human-robot interaction which will be discussed below. Despite the fact that the same personnel may perform more than one of these interactions (Edwards, 1984), they are distinguished by activity rather than operator.

2.1.6.1 Programming

Programming of an industrial robot involves, "...providing the control instructions required for a robot to perform its intended task" (Jablonowski and Posey,1985). More specifically, it involves the input of instructions to the robot computer which determine the actions that the robot will make (e.g. the path of motion), any functions that may be required (e.g. performing a welding operation, grasping an object, etc) and the sequence in which these should occur. The programmer will normally be responsible for programming the robot, test running the program, fine tuning and initial start-up of machine operation after programming (M. Gray, 1984).

There are three basic methods by which programming may be achieved; lead through, teach control, and off-line (Groover and Zimmers, 1984; Klafter et al, 1989). These will be described below.

(i) Lead-through method

In this method the operator grasps a handle which is secured to the robot arm and guides the robot through the desired task or motions. Alternatively, since the majority of robots are too heavy to be moved easily manually, a lightweight replica of the arm, connected to the computer controller may be used. The robot computer records the path of movements made and will accurately retrace the same path with the robot arm. This method is particularly suited for operations such as spray-painting, sealant application or arc welding which require continous-path sequences programmed. The major advantage of lead-through programming is that it is easy to learn and can be performed by an operator who was previously associated with the production task (Deisenroth, 1985). A survey of 50 robotic installations in the USA found that 33% were programmed by this method (SME, 1985).

(ii) Teach control method

This is the most common method currently in use (Cousins, 1988; Parsons, 1988). The American survey found that 50% of robots were programmed using a teach control (SME, 1985). This method involves the operator physically driving the robot arm via a hand-held remote control device known as a teach pendant. The teach pendant is used to position and orientate the tool held by the robot (e.g. welding gun, gripper). When the required position is reached, the coordinates of the robot joints are recorded by the robot computer and stored as a location. These coordinates are replicated when the robot is asked to move to the desired location again. A sequence of locations will determine the path of motions used within the program. It should be noted that the robot will only replicate the exact position of the location itself and will, unless otherwise instructed, take the shortest path between any two locations. Therefore the path of motions during playback of the program may not be the same as that used by the programmer.

(iii) Off-line programming

In this method, the robot control program is created on a computer away from the robot itself and down-loaded to the robot computer when needed. The coordinates of the robot joints for each location can be entered directly into the robot computer without the need to move the robot. Verification of the program may be achieved using a graphic simulation on a computer-aided design (CAD) system. The American survey found that only 11% of robots were programmed in this way (SME, 1985).

This method has important advantages over the other methods primarily because robot downtime can be dramatically reduced as the program can be verified before it is downloaded (therefore increasing robot productivity). A further advantage is that programmer safety may be improved as the programmer spends less time in the robot vicinity (Sorenti and Bennaton, 1989). However, there are problems associated with current off-line programming methods which have led to scepticism over their widespread implementation in the "near-to-middle future" (Humrich and Wilson, 1988). In a study involving 25 robot manufacturers, Humrich and Wilson found that they were reluctant to incorporate off-line programming systems for three main reasons;

1. The potential lack of trained personnel amongst robot users.
2. The current systems developed by academic establishments fail to meet the needs of industry and will not be usable for complex tasks in an industrial environment.
3. The cost of supporting off-line facilities outweigh the potential advantages.

The most common criticism of current off-line programming systems is their lack of standardisation which makes integration with different robots and their associated equipment difficult (Hocken and Morris, 1986; Humrich and Wilson, 1988; Lozano-Perez, 1983; McGee, 1989). On many systems positional data is not accurate enough when entered off-line and this still has to be carried out on-site using a teach pendant (Carter, 1987). Some systems are claimed to have overcome this problem by the use of CAD and sensor calibration (Sorenti and Bennaton, 1989; Tucker and Perreira, 1985). However, the greatest problem is not a shortcoming of the off-line systems but of the robots with which they are communicating; "The lack of precision in robot manufacture and the rigidity of [their] design .. means that no two robots of 'identical' make will respond identically to an off-line programmed instruction" (Irvine, 1986 p. 26).

2.1.6.2 Maintenance

Maintenance tasks will vary depending on the robot, its application and its connected equipment. Also, the range of personnel involved in maintenance work will vary depending on the type of skills required. In general, in the automotive industry, both programming and maintenance work is carried out by personnel with electrical skills (Edwards, 1984). It is usual that routine servicing and maintenance tasks involving tool setting, fault diagnosis, calibration and testing of equipment is performed by in-house maintenance staff but that more serious robot repair work is carried out either by the robot suppliers or specially-trained personnel within the company (M. Gray, 1984).

2.1.6.3 Machine operation

The type of activities performed by the machine operator include initialising the robot system at the beginning of the work shift, loading of workpieces and removal of finished work from the robot work cell, monitoring of robot operation and cleaning of tools, jigs and the general work area (M. Gray, 1984).

All of these tasks will require new skills of the workforce and there is some concern that there may be a large discrepancy in skill levels between the jobs eliminated and those created. Salvendy (1985) suggests that over half of the displaced workers will not possess the right abilities for the new types of manufacturing skills required. This could mean that displaced workers are forced to take on jobs that they are ill-suited to and it has been suggested that the new jobs created by the introduction of robotics may be worse than those which the robot replaced (Schraft and Nicolaisen, 1986).

In a study of 58 robot installations in Sweden, Schraft and Nicolaisen examined the positive and negative aspects for programming, maintenance and machine operation tasks. They used five main criteria for work assessment; safety, stress/strain combination (psychological and physical), work content, work flow and ergonomic design. For each criterion except work content the effects for programming and maintenance were negative (e.g. safety measures were ineffective, physical strain was produced due to bad posture and poor ergonomic design of human-robot interfaces). There were some positive effects for the machine operator (e.g. reduced exposure to the process hazard and reduced physical strain) but even these were offset by the larger number of negative effects resulting from working with the robot (e.g. increased psychological stress, work content more mundane, pace of work fixed by the robot, and inadequate workplace design).

2.1.7 Robot safety

Of the criteria for evaluation of robot installations outlined by Schraft and Nicolaisen (1986), it is the issue of robot safety which has dominated the literature (see Bonney at al, 1985; Lee, 1985; Nagamachi, 1986; Parsons, 1986c; Percival, 1984 for general reviews). These papers or collections represent a few of many within the ergonomics literature which stress concern for 'robot safety'. The main claim is that whilst robots have been acclaimed for taking people out of hostile and difficult work environments, it is becoming increasingly apparent that robots themselves are dangerous and can be the cause of human injury in industry. For clarity, the safety issues associated with each type of human-robot interaction will be discussed separately.

2.1.7.1 Programming

The teach control method of programming has produced some concern for the safety of the programmer since it is often necessary for the programmer to be in close proximity to the robot arm during movement (Munson, 1985; Schraft and Nicolaisen, 1986). Parsons (1988) describes how a programmer of robotic welding needed to be within a few inches of the weld for precise alignment of the tool, "For safety," he says, "he kept one hand on the robot so he could immediately feel if it started to move unexpectedly" (p.750). Obviously, any errors in robot motion control at such a time could have serious consequences resulting in damage to the robot or other equipment or worse, injury to the programmer.

Another concern for programmer safety, is that during test running of the program, the programmer may not accurately predict the path of motion between two locations. This, again, could result in damage or injury.

It has been argued that one advantage of the off-line programming method is improved programmer safety as it reduces the need for contact time with the robot (Sorenti and Bennaton, 1989). However, it may still be necessary to test and fine-tune the program using a teach pendant at the point of operation.

2.1.7.2 Maintenance

As with programming tasks, the maintenance engineer may need to work within the robot work area with motive power available in order to check the functioning of parts (Bray, 1987). In this case, the same hazards during programming apply during maintenance and there have been some cases of unexpected robot start-up when a fault occurred in the robot communication system (ILO, 1982). The most common problem for the safe operation of maintenance tasks, however, is the general lack of space within the robot work area causing trapping points (M. Gray, 1984).

2.1.7.3 Machine operation

Within the U.K. there are strict regulations governing the access conditions to the robot work area during machine operation (HS/G 43, 1989), and consequently this is expected to be the least hazardous type of human-robot interaction. However, if for any reason the operator should by-pass safety precautions and enter the robot cell during machine operation, then the potential hazards are extremely serious. It is under these conditions that some operators have been 'killed by robots'.

2.1.8 Accident reports

The media reports of those deaths involving robots have been somewhat sensationalised, portraying the robot as a dangerous 'man-killer' with a taste for blood (see Figure 2.2). In truth, however, the causes of robot-related accidents are more usually associated with 'human error', directly or indirectly.

The first fatal accident involving an industrial robot occurred in Japan in 1981 (Nagamachi, 1986). During machine operation, the worker noticed that the robot had stopped as it was waiting to load material into an abrasive machine but had not received the signal to do so since the door on the abrasive machine was jammed. The worker took off the safety rope to enter the work area, cut the switch relating to robot movement and switched the abrasive machine to manual whilst he fixed the door. He then turned the abrasive machine back to automatic and "carelessly turned on the robot operation switch" (p.11). With the door to the abrasive machine fixed, the robot received its signal to load the machine and moved forward crushing the worker into the machine.

There is no information given as to the location of the robot operation switch or how this could be 'carelessly' switched on. However, it is clear that in this case the robot was not quite the 'demon bloodhunter' suggested by the press, but was merely performing its programmed task. The accident was the result of 'human error', both on the part of the worker not carrying out the correct entry procedure, and also on the part of the company which provided insufficient guarding to restrict the worker from the robot area.

In America, NIOSH (1984) reported on the death of a worker who was crushed by a robot against a ‘safety’ limit-stop pole. It appears that the man had climbed over, through or around a safety rail which surrounded two sides of the robot’s work area in order to clean up scrap metal that had accummulated on the floor behind the robot. Although the report concluded that the cause of the accident had been the worker's failure to follow the appropriate entry procedure, a $10 million compensation claim was awarded against the company and to his family, on the grounds that the robot guarding was insufficient (Computerworld, 1983).

Figure 2.2 Newspaper reports of robot-related accidents

TYRANNOSAURUS TECHS

ROBOT MURDERS

On the fourth [illegible]
[illegible]

The Village Voice (1987)

Monster robot savages workers

HI-TECH violence came to Ford's factory in Southampton today when two men were attacked — by a

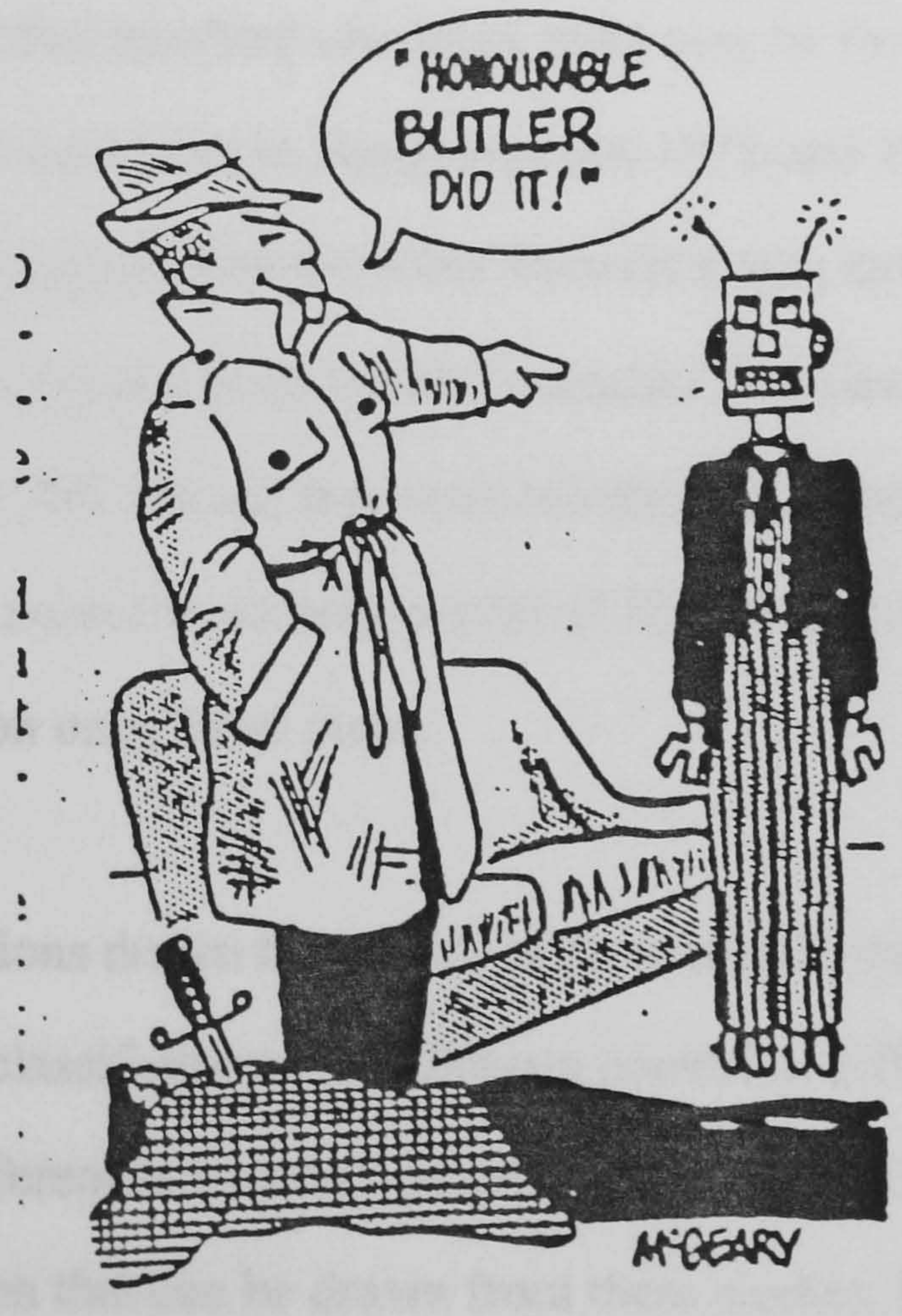
Southern Evening Echo (1987)

Car-line worker attacked . . . by a robot

News on Sunday (1987)

Robots with the killer instinct

Source unknown



been given by a human minder.
The first reported "murder" occurred in 1981 when a fac-

Despite the concern for worker safety that is stimulated when deaths such as these occur, there have actually been very few reported accidents involving industrial robots. Unfortunately, this does not necessarily reflect low risk-levels but more likely is the result of under-reporting of accidents (Ryan, 1988).

The accident surveys that have been documented reach different conclusions as to the type of human-robot interaction that is most hazardous. In Sweden, Carlsson (1985) conducted a 14-day study in which 36 accidents were recorded. 70% of these occurred during programming. A survey in Japan (Sugimoto, 1977) also showed that accidents were most likely to occur during programming or teaching (49.8%). Unfortunately, the report does not state the number of cases or sites' surveyed and so it is impossible to know how many accidents these refer to. In France, a national survey sent out to industries yielded 102 responses (Vautrin and Deisvaldi, 1986); 70% of the respondents indicated that they had experienced danger during programming although no details are provided.

Other studies suggest that machine operation tasks may be the most hazardous; Sugimoto (1985) reported that of 11 accidents in Japan between 1978 and 1982, 8 of these occurred when a machine operator approached the robot because it was moving slowly or had stopped. In a reanalysis of accident reports from several countries (Sweden, West Germany, Japan and USA), Jiang and Gainer (1987) found that most accidents occurred during machine operation. Unfortunately, their report considered only a total of 32 accidents and a comprehensive analysis was performed on only 24 of these.

The different conclusions drawn from each of these studies may be due to differences in human-robot interaction classifications for different countries, differences in the nature of the interactions involved, differences in safety policies and differences in accident data assessment.

The general conclusion that can be drawn from these studies, however, is that all human-robot interactions are potentially dangerous to personnel. The causes of accidents have been identified as being primarily due to (Jiang and Gainer, 1987):

i) failure of safeguards (these may be inadequate for the application or may even fail to operate effectively)
ii) human error (e.g. incorrect control input during programming or abuse of the safety procedures)

These researchers concluded that the accidents caused during machine operation could have been prevented by the provision of better guarding but, that other measures must be applied to ensure safety for programmers and maintenance workers.

2.1.9 Safety measures

Numerous recommendations for robot safety are reported for specific applications (Hamilton and Hancock, 1986; Hartmann, 1986; Linger, 1985; Macek, 1981), but guidelines for robot safety tend to be in general terms (ANSI, 1986; HS/G 43, 1989; JISHA, 1985). It is the very nature of the problem of robot safety that causes this; every robotic installation is different and therefore has slightly different problems regarding safety. Recommendations that work in one situation may not be applicable to another.

2.1.9.1 Programming

It has already been stressed that the programming task presents an additional set of conditions that are directly related to human safety; in most instances, the programmer will have to work within the robot's movement range in order to teach it its task. Spatial locations requiring precise positioning usually require the programmer to be close to the manipulator arm. An important safety feature that is implemented in all robot systems is the enforced restriction on speed and power available to the robot arm during teach control (Munson, 1985). There has been much research carried out in Japan to establish standards for safe motion speed via the teach pendant (Etherton et al, 1988; Etherton and Sneckenberger, 1990; Karwowski et al, 1987; National Safety Council, 1985; Van Deest, 1984). These experiments support current standards which are set at 0.25m/s (ANSI, 1986; HS/G 43, 1989; JISHA, 1985).

Other safety features that are included on the teach pendant are; use of the teach pendant automatically overrides control from the robot controller panel, there should be a hard-wired emergency stop button which immediately removes power to the robot arm, and the motion controls should be of the 'hold-to-run' type which will stop arm movement as soon as they are released (ANSI/RIA, 1986; HS/G 43, 1989).

It is recommended that testing of the robot program should be treated as 'machine operation' and performed under the same conditions; outside of the robot work area if possible (Munson, 1985).

2.1.9.2 Maintenance

For routine servicing and planned maintenance there should be a means of properly isolating and locking out the actuating power supplies (e.g. electrical, hydraulic or pneumatic) (HS/G 43, 1989). Some manufacturers provide a manual control pendant which permits movement of the arm but with no power to the robot's control system (Munson, 1985).

One recommendation that has been made to improve safety for the maintenance engineer is that an information system on cell status should be provided (Bray, 1987). This, he claims, should limit the number of times that a maintenance engineer must enter the robot cell. Other advantages are that it may enable more efficient repair when computer diagnostics have identified a problem and thereby facilitate preventive maintenance. Current regulations recommend that if it is necessary to perform troubleshooting inside the robot area with arm power on, a safe system of work must be utilised. This involves two men being present, one to carry out the troubleshooting, and the other to keep an eye on the robot and be ready with an emergency stop button (HS/G 43, 1989).

2.1.9.3 Machine operation

In the UK there are strict regulations requiring complete enclosure of a robot work area by means of 2 metre high fixed guarding (HS/G 43,1989; MTTA, 1982). The guarding should completely enclose the robot work area but care must be taken to ensure that there is sufficient room to move freely within the area such as during programming or maintenance. The most common type of barriers used are fences and gates that restrict access to a robot work area;

generally, they are adaptations of standard machine guards. Various types are available depending on the type of access required, including; fixed barrier guards, limited opening barriers, and interlocked movable barriers (DeReamer, 1980). At points of material flow into and out of the work area, some type of presence-sensing device may be used to detect human entry during machine operation, including pressure mats, photoelectric light barriers, cameras, etc.(Briggs and Rahimi, 1986; Graham, 1985). These presence-sensing devices will act in the same way as an interlock gate which will allow human access to the robot area. When the interlock is broken (i.e. the entry gate is opened) or a sensing device detects intrusion into the area, the robot program is immediately halted and power to the robot arm is removed.

In other countries, however, guarding measures are less stringent, although there are usually some efforts to keep personnel away from the robot's movement range. A survey in Japan found that, of 190 robot installations, 89.5% had provided safeguarding but that 30% of these were ineffective barriers such as a rope or 'keep out' sign (Sugimoto, 1985).

2.2 Teach Control

Teach control is the method of robot programming via a remote teach pendant device. This enables the programmer to move freely within the robot work area whilst setting up the control program for the robot operation. Typical examples of teach pendants are shown in Figure 2.3. These represent the two main types of control design; joystick and pushbutton control. They are described in more detail in section 3.4.

There are two basic functions that the teach pendant is used for;

i) motion control.

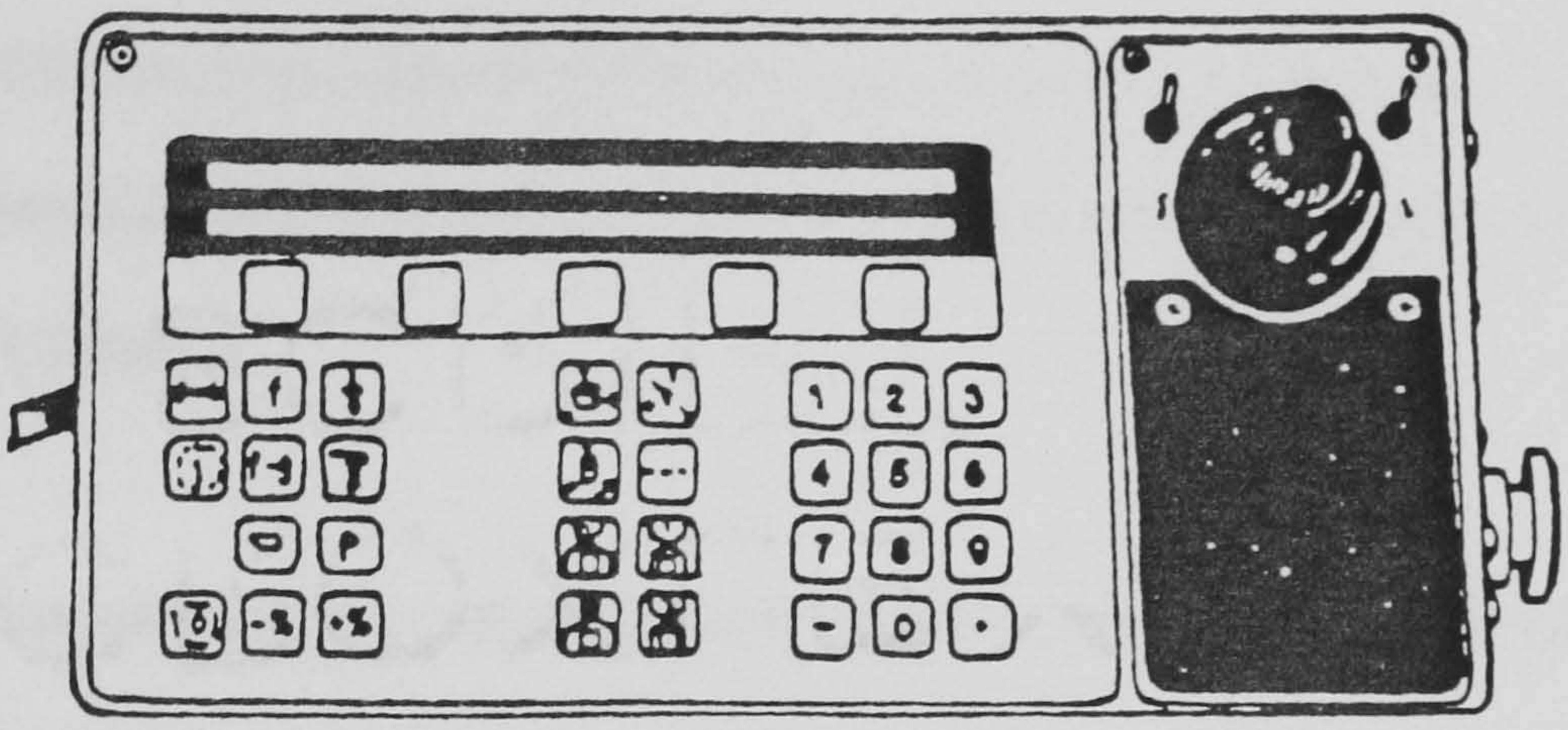
This involves physically 'driving' the robot arm to the required locations which will determine the path of motion of the robot arm during operation of its task.

ii) program control.

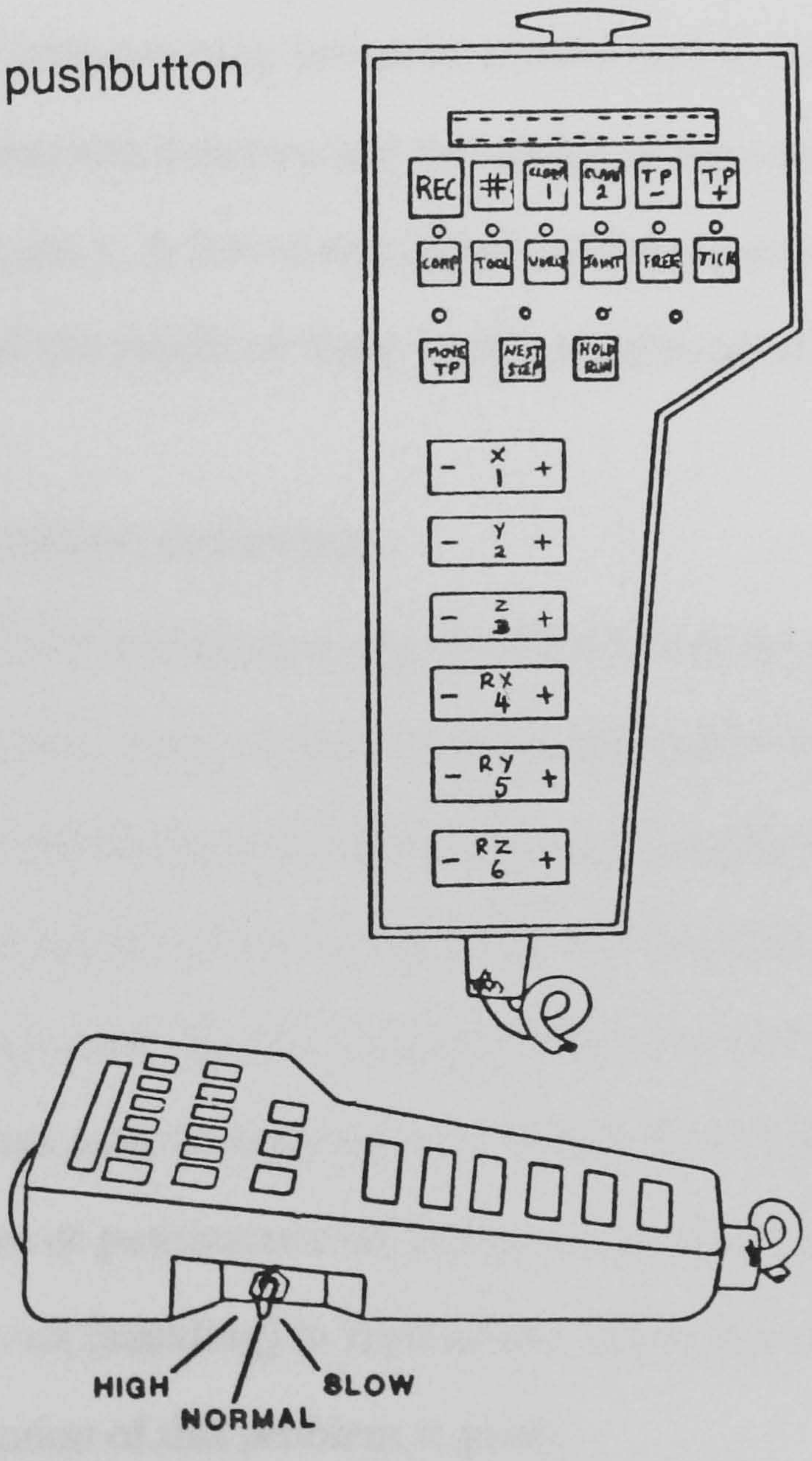
This involves the input of command instructions governing how the robot arm moves between the recorded locations and what functions or operations are to be performed at each.

Figure 2.3 Two alternative teach pendant designs (joystick and pushbutton)

joystick



pushbutton



Program control is an important part of the teach control process but, depending on how much of it is performed via the teach pendant itself, need not take place within close proximity to the robot arm. Motion control, on the other hand, most certainly does take place in close proximity to the robot, sometimes just a few inches away from the tool (Parsons, 1988). For this reason, and in order to make feasible the experimental process, the motion control aspect of teach programming has been selected as the primary concern and therefore the focus of attention in this thesis.

As already mentioned, the potential for human-robot collision while using the teach pendant for robot motion control has led to concern for programmer safety and this is particularly so in situations where the programmer operates more than one type of robot (Edwards, 1984; Helander and Karwan, 1988). There is great variety between teach pendants currently used for programming industrial robots, both in terms of the method and amount of program control they can achieve, and the design of the controls used (e.g. layout and type of controls, displays, etc.). A few researchers have investigated the differences between different teach pendants and the results of these studies are discussed below.

2.2.1 Teach Pendant evaluation

Levosinski (1984) carried out a survey of more than ten teach pendants. The criticisms he made were as follows; many of them were too large and too heavy, necessitating the use of both hands just to hold them, those that were used for program control often had a large number of keys or buttons which increased the likelihood of the programmer making an incorrect control selection, the more sophisticated teach pendants also used a membrane keyboard rather than push-to-make buttons, which did not provide sufficient tactile feedback of activation. The use of pushbuttons for motion control Levosinski criticised on the basis that; "If the operator is not [standing] in front of the robot, directions can be goofed up" (p.599). No further explanation of this problem is given.

Levosinski recommended an alternative design of teach pendant based on general ergonomic principles. The criteria implemented in the new design were as follows; The use of as few keys as possible to minimise the decision-making process of the operator, the use of colour and location grouping to indicate different function keys, tactile feedback, and the use of a joystick for X,Y,Z motion control. No mention is made of the size or weight of the new pendant.

Unfortunately, this article is very brief and it is difficult to ascertain the depth or quality of the survey performed. It is stated that the new teach pendant was designed for a specific robot system, but no information is given as to what make or type of robot this was. No comment is made on the applicability of the recommended design to the alternative robot systems investigated. It appears that Levosinski derived the design criteria from general text books and gained no empirical measure of performance improvement using the new teach pendant. It is stated that the recommendation for joystick use is based on testing adults and children using video joysticks, but no details are given.

A much more comprehensive study of robot teach pendants was carried out in the USA by Parsons and Mavor (1986). Ten robot manufacturers were consulted for the study which provides detailed descriptions of the teach pendant designs and their functions. A task analysis of the procedure of teach control was performed as well as an assessment of the control manuals for each robot system. The report comprises a 98-page data base of robot programming interfaces, 55 of which are dedicated solely to the ten teach pendants. The findings of this survey are summarised in later papers (Parsons, 1986a; 1988), the main features of which will now be presented. The teach pendants were found to vary in size and shape and in the method by which they should be held; larger pendants would be rested on the programmers' forearm whereas smaller ones could be more easily held in the palm of the hand. Some pendants had cord or finger grips to prevent dropping and consequent damage. Most pendants had a liquid crystal display (LCD) but there was considerable variation in the number of lines and characters displayed as well as the content of displayed information. The number of buttons on the teach pendants ranged between 21 and 46 and the number of functions which may be input by these buttons ranged from 25 to 89; six of the pendants utilised multifunction keys. For motion control, two of the pendants used a 3-axis joystick and the rest used either 6 or 12 buttons. Most of the pendants used some form of grouping, either by colour or spatial arrangement (e.g. rows) although only three had made use of spatial separation. On most of the pendants labelling was in words or abbreviations although ASEA have developed a system of symbolic representation for function keys. Feedback of control input is provided in various ways; on three pendants a light emitting diode (LED) would be illuminated when a key was pressed, two provided tactile feedback, one produced beep noises and on the others the input was displayed on the LCD.

The conclusions of this study were that no two teach pendant designs are alike and that the consequence of such design diversity is that some design aspects will support better programming performance than others.

Elsewhere, Parsons (1986b) has stressed the lack of ergonomic considerations in robot programming interfaces. Although the terms "ease of use" and "user-friendly" frequently appeared in the brochures describing the robot control system, Parsons and Mavor (1986) found little evidence of empirical assessment of teach pendants among robot manufacturers. The one exception is in the experimental tasks carried out by ASEA for the introduction of their joystick teach pendant (Brantmark et al, 1982). The justification of using a joystick in place of pushbuttons for controlling robot motion was that; "A joystick gives a movement, whose direction and speed are determined directly by its deflection. This ensures a fast, natural and sure positioning of the robot, which in turn means both a shorter programming time and better safety" (p.147). These claims were allegedly supported by the results of experimental tests comparing the joystick with a pushbutton design, performed by both trained and untrained programmers. It was reported that there was an average 25% reduction in positioning time using the joystick and that the untrained operators learnt more quickly using the joystick. Unfortunately the article provides no information as to how many programmers carried out the test nor any details of the programming task and the analysis methods used.

Parsons (1986b) also points out that the extent of interest in ergonomics by robot manufacturers for teach pendant design is limited to the grouping of buttons and some use of colour coding. The extent of interest in robotics by ergonomists is, as Parsons claims, relatively recent and as yet has had little impact despite the establishment of a Human Factors and Safety Division within Robotics International, a component association of the Society of Manufacturing Engineers.

Despite this claim, some efforts to introduce ergonomics to the design of robot teach pendants has been made by standards committees and these will be discussed in the folowing section.

2.2.2 Teach Pendant Design Standards

"In 1984, the Robotic Industries Association [in America] created the R15.02 Robot-Human Interfaces Subcommittee...[whose aim was to] create a design standard to specify human factors criteria for robot teach pendants. The purpose of the standard was to promote uniformity, effectiveness, simplicity, efficiency, reliability and safety of operation with robot pendants." (Cousins, 1988 p. 429). The proposed standard was completed in 1988 (ANSI, 1988).

Initially, the RIA sent out a questionnaire to robot manufacturers, suppliers and users to determine what aspects of human-robot interaction needed most attention. The results suggested that standards relating to robot interfaces should be given high priority. The R15.02 subcommittee assessed 26 different robot teach pendants and concluded that there was a need for standardisation in teach pendant design.

As mandatory requirements, the proposed standard calls for smaller, lighter teach pendants using the simplest design for their functional requirements, which personnel with a minimum of training would be capable of operating. As a general requirement, the "controls and displays [should] be appropriately and clearly labelled with the basic information needed for proper identification, utilisation, actuation or manipulation" (para. 9.5.1). On control design it requests definitive feedback of control actuation, that the controls should be arranged such that accidental operation is prevented, and the minimum essential number of controls are used, adding; "Whenever justifiable and feasible, two or more controls should be combined into one." (para. 5.1.8). On motion control it is recommended that; "labelling [on controls should] be unambiguously displayed for positive and negative directions for each degree of freedom associated with each [programming mode]." (para. 4.5.1). Furthermore, the controls should be designed such that; "Actuation of a control corresponds to the expected control-movement direction, and be oriented so that the control motions are compatible with the movements of the [robot]." (Para. 5.3.1).

The proposed RIA standard provides design criteria for a range of control types (e.g. joystick, trackball, knobs, toggle switches, pushbuttons, etc.) in terms of size, resistance, displacement and separation from other controls. However, no guidance is provided as to which type of control is best suited to robot motion control.

In the U.K., guidelines published by the Health and Safety Executive (HS/G 43, 1989) also advocate ergonomic design of robot teach pendants; "The application of ergonomic principles to the design of teach pendants can improve safety by simplifying tasks and reducing the scope for human errors." (para. 38.). Many of the recommendations are similar to those in the RIA proposals; the pendant should be as small and light as possible, the number of controls should be kept to a minimum, controls should be adequately spaced to prevent accidental operation, labelling should be clear and simple, etc. However, they do not agree with the use of multifunction controls as; "[They] are confusing and slow to use and should be avoided on a teach pendant where possible, especially on controls causing robot motion." (para. 42). The problem of the compatibility between control and robot movement direction is addressed on a perceptual basis; "The operator must know where to stand in relation to the robot in order to obtain the correct control orientation [as] robot-left is not always operator-left". It is suggested that; "Aids to orientation, including floor marking, can assist in correct use of the teach pendant." (para. 50).

Japanese standards (JISHA, 1985) refer mainly to safeguarding and operational procedures although some mention of the teach pendant is made. They recommend that slow speeds are used when programming and to aid correct movement control, they suggest that; " The direction of each axis is marked upon the robot itself and in a similar way on the teach pendant controls." (para. 2.1.9, p.44).

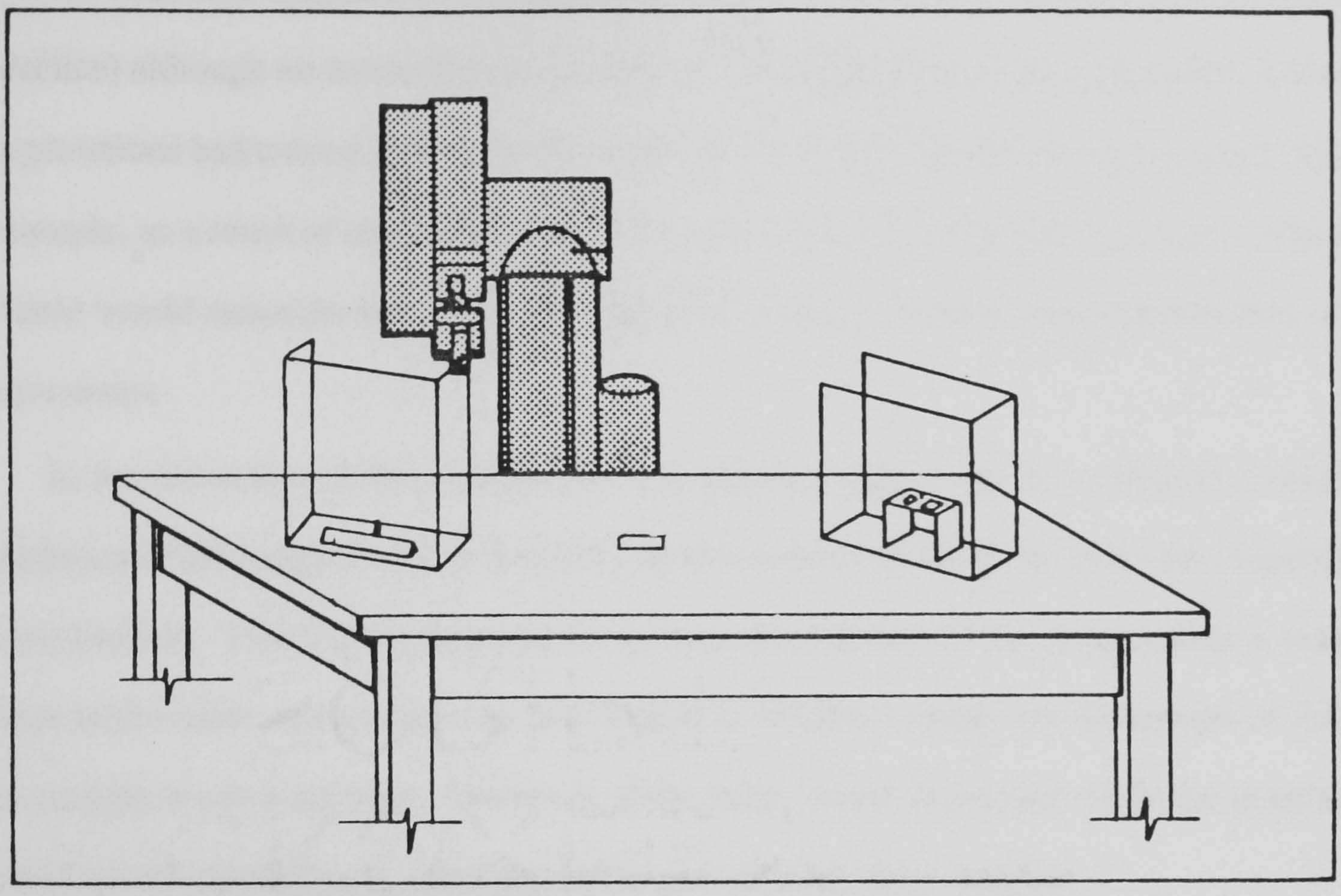
It is clear from these guidelines that there is some concern for the design of robot teach pendants to be improved ergonomically and eventually standardised in order to minimise the potential for human error. With regard to motion control, however, the guidelines offer no recommendations about which control design is preferred or what axis labelling method should be used. The problem for the safety authorities is that they cannot easily choose the best attributes from current teach pendant designs, thus making standardisation difficult.

2.2.3 Experimental evaluations of motion control performance

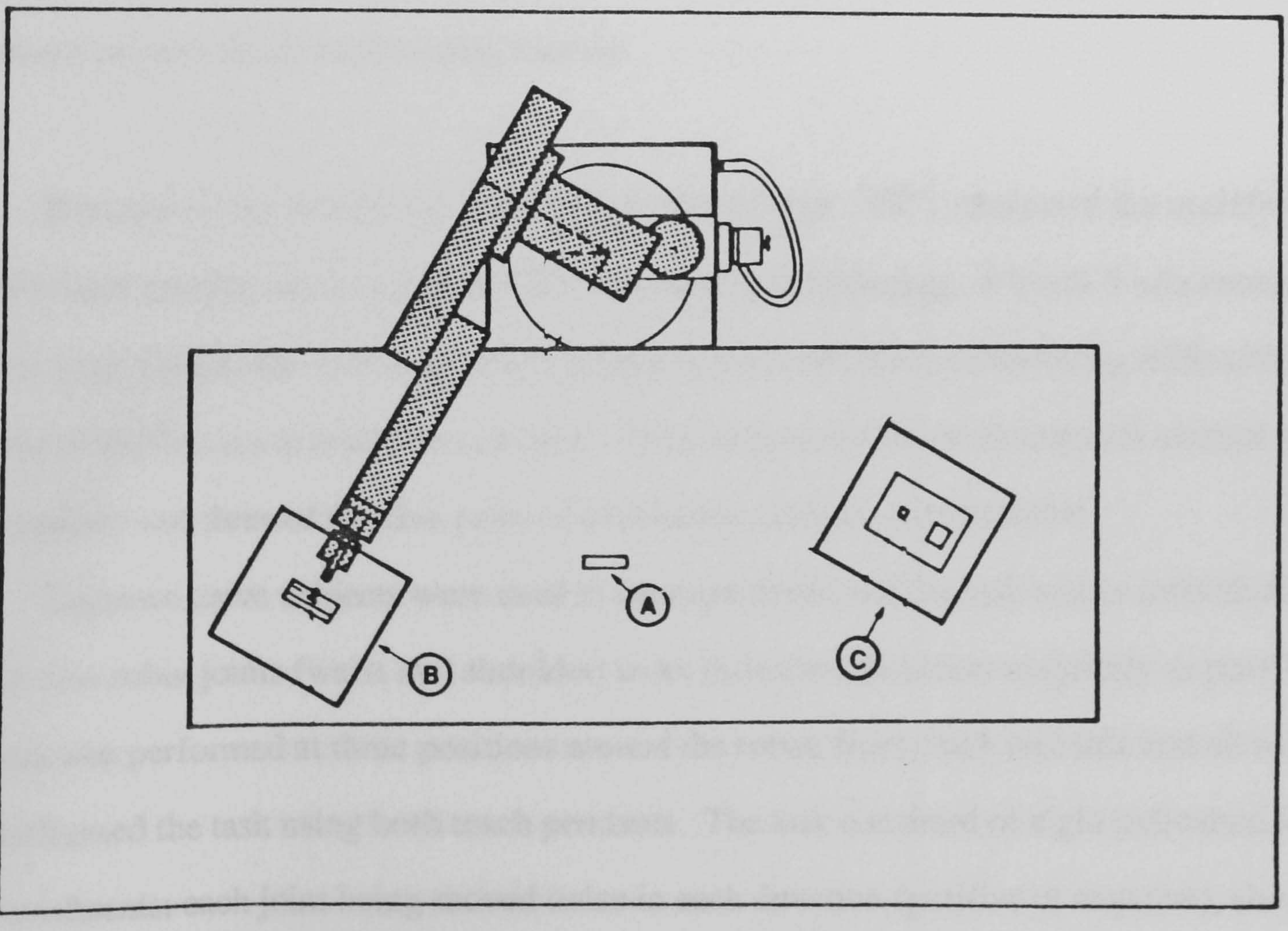
Limited research is currently being conducted to measure motion control performance (in terms of speed and accuracy) using different teach pendant designs. Two designs in particular have been experimentally examined by various researchers; the Unimate pushbutton teach pendant and the ASEA which uses a joystick for motion control (previously illustrated in Figure 2.3). The researchers hope to offer empirical evidence from which the 'best' design of robot motion controls can be recommended.

In Canada, Ghosh and Lemay (1985) assessed the usability of the Unimate pushbutton teach pendant. Ten naive subjects were used to perform an experimental task which involved gross robot arm movement and manipulation of the gripper to pick up and orientate a tool object as seen in Figure 2.4. Starting from point A the subjects were instructed to manipulate the robot arm to pick up a peg at point B and insert it into a square hole at point C. This task involved movement of the robot in both JOINT and TOOL programming modes (described in section 3.2) and was repeated 30 times. The independent variables measured were time and accuracy. Two types of performance errors were identified; contact, whereby the robot arm or workpiece touched an obstacle; and non-contact, whereby the robot arm moved away from its destination rather than towards it. The subjects were trained in the use of the teach pendant and given guidance on the best path of motion required to complete the assigned task. It would appear from the diagram (Figure 2.4) that the subject would be positioned at the left side of

Figure 2.4 Experimental set-up used by Ghosh & Lemay (1985)



Observer's view of the experimental task



Plan view of the task

the robot (judging by the position of the motor) although this is not stated by the authors.

The results show a learning curve for time to complete the task which stabilised after 20 cycles. A similar shaped curve represented the error rate (i.e. performance improved with practice) although no actual figures are given. The authors noted that population stereotype expectations had caused difficulty for some of the subjects during the experiment. For example, as a result of the orientation of the tool, there was a specific position where the ' Z-' button would move the tool vertically upwards, contrary to the anticipated direction of movement.

In the discussion of this experiment, the authors suggest that the confusion arises from a tendency of the programmer to interpret the movements of the robot arm with respect to his/her own position. This is demonstrated by an example whereby if the programmer is standing in front of the robot and presses the 'Y+' button in WORLD mode, the movement of the tool will be straight towards him/her. However, if the same button is pressed while the programmer is standing behind the robot, then the tool is moved away from him/her.

They concluded that, if a programming task involves movement of the programmer around the robot, unsafe situations may be created if the programmer is uncertain as to which control would produce the intended robot motion.

Research at the Health and Safety Executive (Creed, 1987), compared the usability of these two teach pendant designs in the JOINT mode of programming. A small 5-axis research robot was used for the task with both teach pendants; however, due to interfacing difficulties, only two of the five joints could be operated. Thus, only two axes on the joystick control were operative and three of the five pairs of pushbutton controls were inactive.

Eighteen naive subjects were used in the experiment and the task was to individually move the two robot joints (waist and shoulder) in an instructed direction as quickly as possible. This task was performed at three positions around the robot; front, back and side and all subjects performed the task using both teach pendants. The task consisted of eight individual joint movements; each joint being moved twice in each direction (positive or negative), always starting from the robot's 'centre position' which allowed for randomisation of movement sequence. An A4 board was held up to indicate the direction of movement required and the subject was instructed to select and activate the appropriate control as quickly as possible.

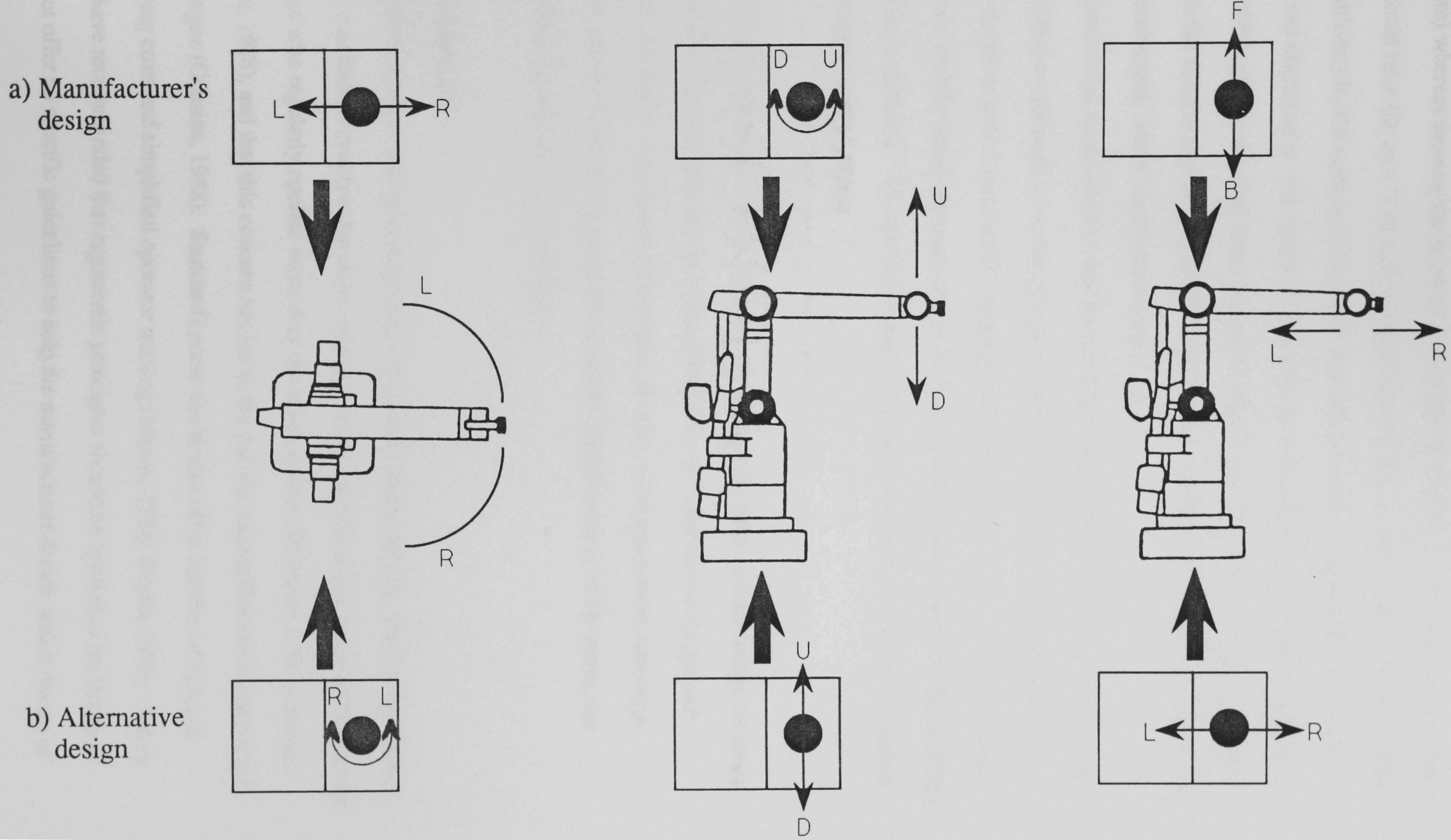
The results indicated that the joystick pendant produced more correct control responses at the front and back of the robot (24% and 19% more correct responses respectively), but that the pushbutton pendant produced better performance than the joystick at the side position (12% more correct). Furthermore, the joystick pendant produced virtually no errors at the front of the robot, compared with 25% errors using the pushbuttons. However, in all other operator-robot orientations neither pendant was considered satisfactory (25-44% error rate).

In Poland, the lack of any ergonomic guidelines for the design of robot teach pendants prompted research at the Department of Ergonomics in the Central Institute for Labour Protection (Podgorski and Boleslawski, 1990). It appears that Polish industrial robots (referred to as IRp) utilise a joystick teach pendant very similar to the ASEA pendant which was shown in Figure 2.3b. Podgorski and Boleslawski (1990) evaluated two aspects of the teach pendant; the control-motion relationship between the joystick and robot motion, and the layout of the control panel used for program control. As a result of their study, they produced recommendations for design change on both aspects. For reasons mentioned earlier only the motion control study will be described here.

The joystick control-motion relationship was evaluated by experimentation in which ten subjects were trained to use the joystick for robot positioning and then were instructed to perform 15 successive cycles of positioning the robot end effector at three marked locations around the robot (no further details of the task are given). The IRp robot is a jointed parallelogram type of robot and only the first three degrees of freedom were used in the experiment (robot types and degrees of freedom are described later in section 3.1).

Two variations of the joystick design were compared for speed of task completion. One design was that recommended by the manufacturers which uses the control-motion relationship shown in Figure 2.5a. The other used an alternative control-motion relationship proposed by the experimenters (see Figure 2.5b). The design assumptions for the alternative arrangement were that the rotary movement of the joystick should induce rotary movement of the robot

Figure 2.5 Joystick control labelling examined by Podgorski and Boleslawski (1990)



(i.e. the base) whereas moving the joystick to the right should extend the robot and moving it forward should raise the arm. It should be noted that only part of the diagram given in Figure 2.5 was published by the authors as they had only described the manufacturer's joystick design but not illustrated it. For clarity of comparison, both designs have been illustrated in Figure 2.5 although it is not clear from the article which way the joystick would normally be held. If it is the same as the ASEA pendant then the axes labelled L/R and F/B in Figure 2.5a should be exchanged, which would seem more logical.

The experimental results showed that the alternative design produced an average of 18% faster performance (although no actual figures are given) and that the subjects preferred the alternative design because it was easier. Judging from the diagram (Figure 2.5) this would certainly seem to make sense although the previous comments regarding the labelling of Figure 2.5a should be considered. No mention is made of human-robot orientation or the range of movements used within the task.

All these experiments have led to mixed opinions as to the most suitable design for robot motion controls. This may possibly be due to differences in experimental design and interpretation of results. A common observation, though, is that population stereotype expectations, and the effect of changing the operators' position vis-a-vis the robot, can adversely effect the use of motion controls.

2.3 Conclusions

The variation in teach pendant designs has been clearly demonstrated. Furthermore it has been shown that there is concern that these types of control variations may cause difficulties for programmers who regularly operate more than one robot system (Edwards, 1984; Helander and Karwan, 1988), and that this concern has led to the call for standardisation in robot teach pendant designs (Cousins, 1988). Standardisation would also offer benefits of reduced manufacturing costs and simplified operator training (Mason, 1986; Smola, 1986). Safety authorities have recommended that ergonomic principles should be applied to the design of pendants, but offer no specific guidelines to help the manufacturer decide which design of motion control is preferable (ANSI, 1988; HS/G 43, 1989; JISHA, 1985).

Experimental evaluation of the two main types of motion control (pushbutton vs joystick), has not produced sufficient evidence to determine which one is 'best' as they each offer different advantages (Brantmark et al, 1982; Creed, 1987; Ghosh and Lemay, 1985; Podgorski and Boleslawski, 1990). This is most likely due to variations in experimental design and analysis techniques. The literature has, however, provided some information on the factors that contribute to motion control errors; i.e. population stereotype associations between the controls and robot movement are expected, leading to confusion when the control-motion relationship is incompatible.

It is concluded that, although teach pendant design and variation is an important issue in performance reliability, other factors may also be influencing performance. One such factor is human-robot orientation which is thought to add complexity to the task (HS/G 43, 1989). It is the intention of the present research to examine factors such as human-robot orientation to determine why they increase task complexity and what the consequences for performance reliability might be.

CHAPTER 3 - PRINCIPLES OF ROBOT MOTION CONTROL

CHAPTER 3 - PRINCIPLES OF ROBOT MOTION CONTROL

3.0 Introduction

Any assessment of task complexity during robot motion control, and of influences upon this, requires an understanding of the task itself. However, before a detailed examination of the robot motion control task can be made, it is necessary to first define some principles of robot motion and control. This chapter explains robot movement and how teach pendants are used to achieve these movements. An understanding of these principles is necessary for the reader to appreciate the research method adopted by the author in the following chapters.

3.1 Robot types

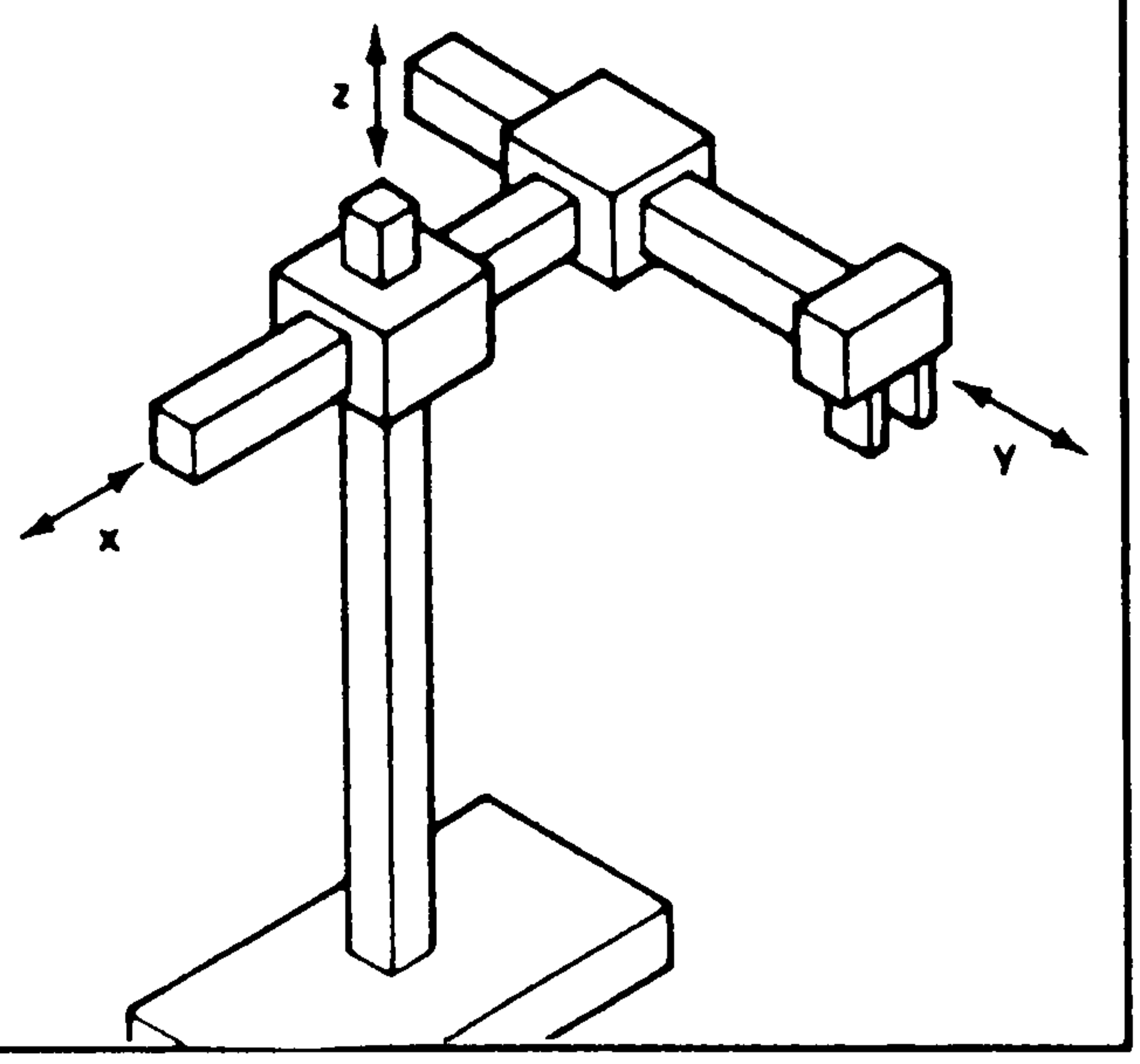
In order to move from one position to another, the robot makes use of its major axes; consisting of two or three joints. Each joint represents an independent motion of the robot and the number of joints it has define its degrees of freedom (DOF). The motions that these joints provide can be either of two types;

1. Revolute motion. This produces a pure rotary motion and a joint of this type is described as a rotary joint.
2. Prismatic motion. This produces pure linear or translational motion and a joint of this type is described as a linear joint.

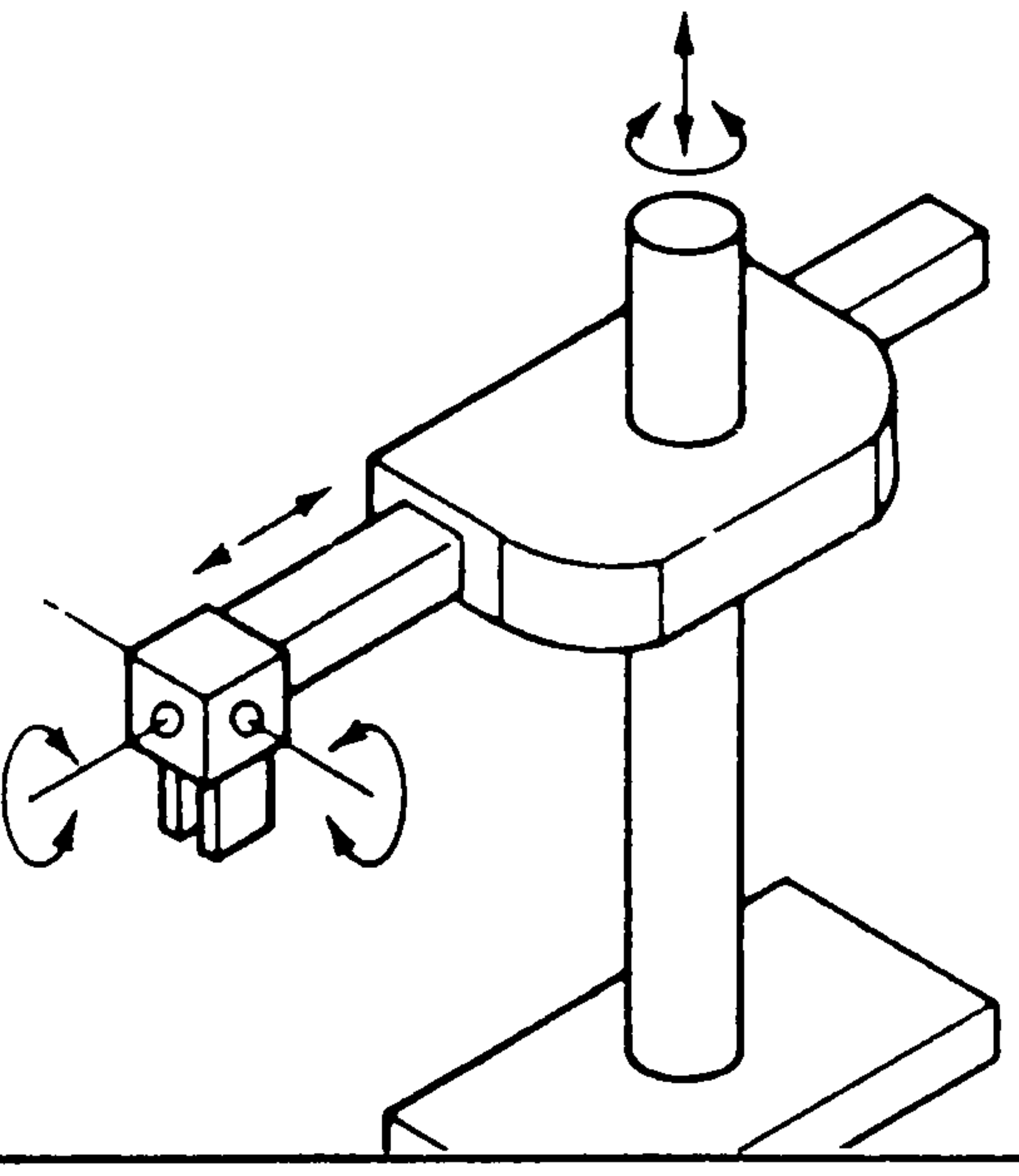
Although there are a variety of robot designs available, they are generally classified as being one of four basic types each of which defines the combination of rotary and linear joints in the major axes (Engelberger, 1980; Groover et al 1987; Lammineur and Cornillie, 1984). The four main robot types are illustrated in Figure 3.1 and described below.

Figure 3.1 Robot types

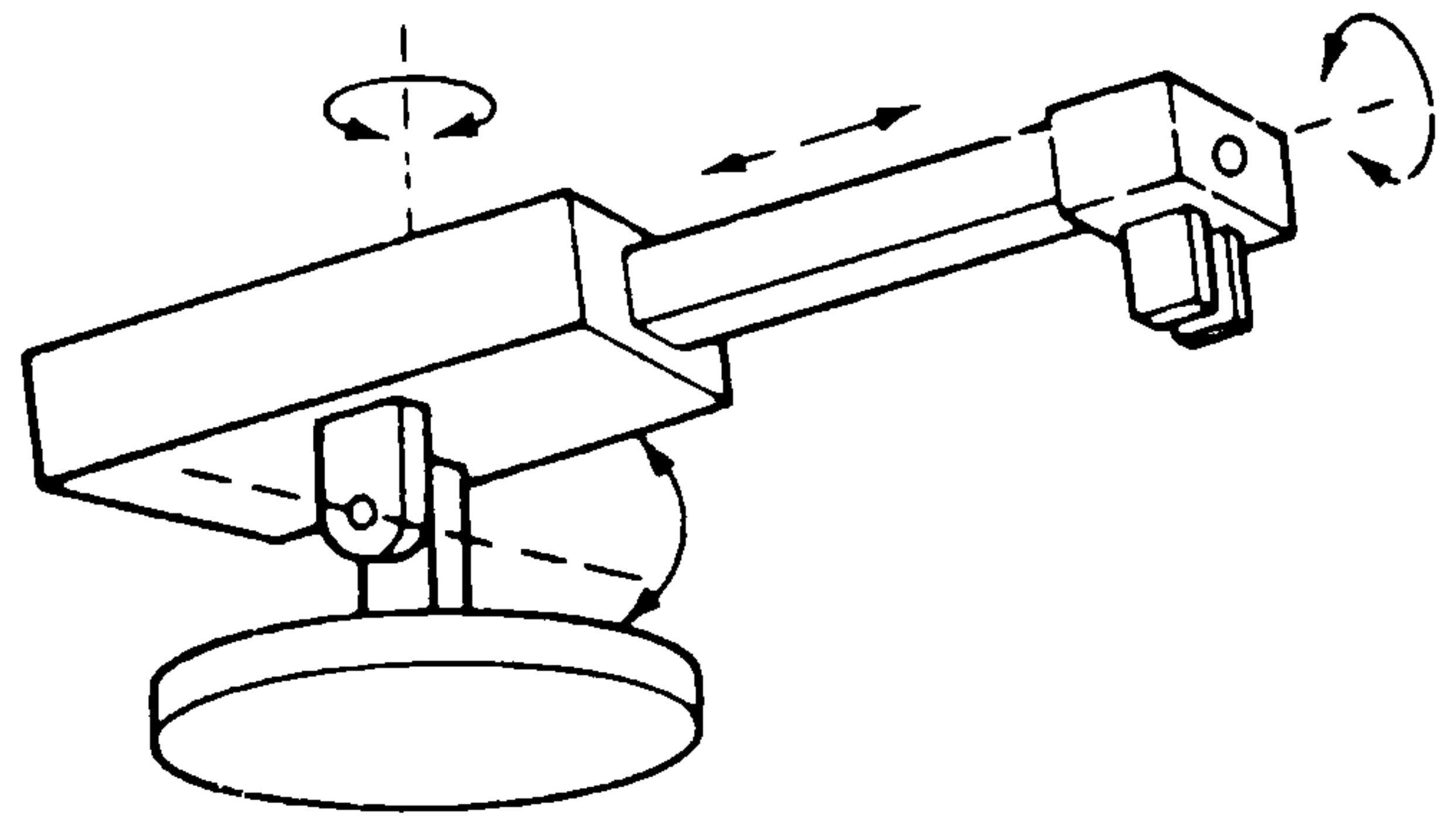
a) cartesian coordinate



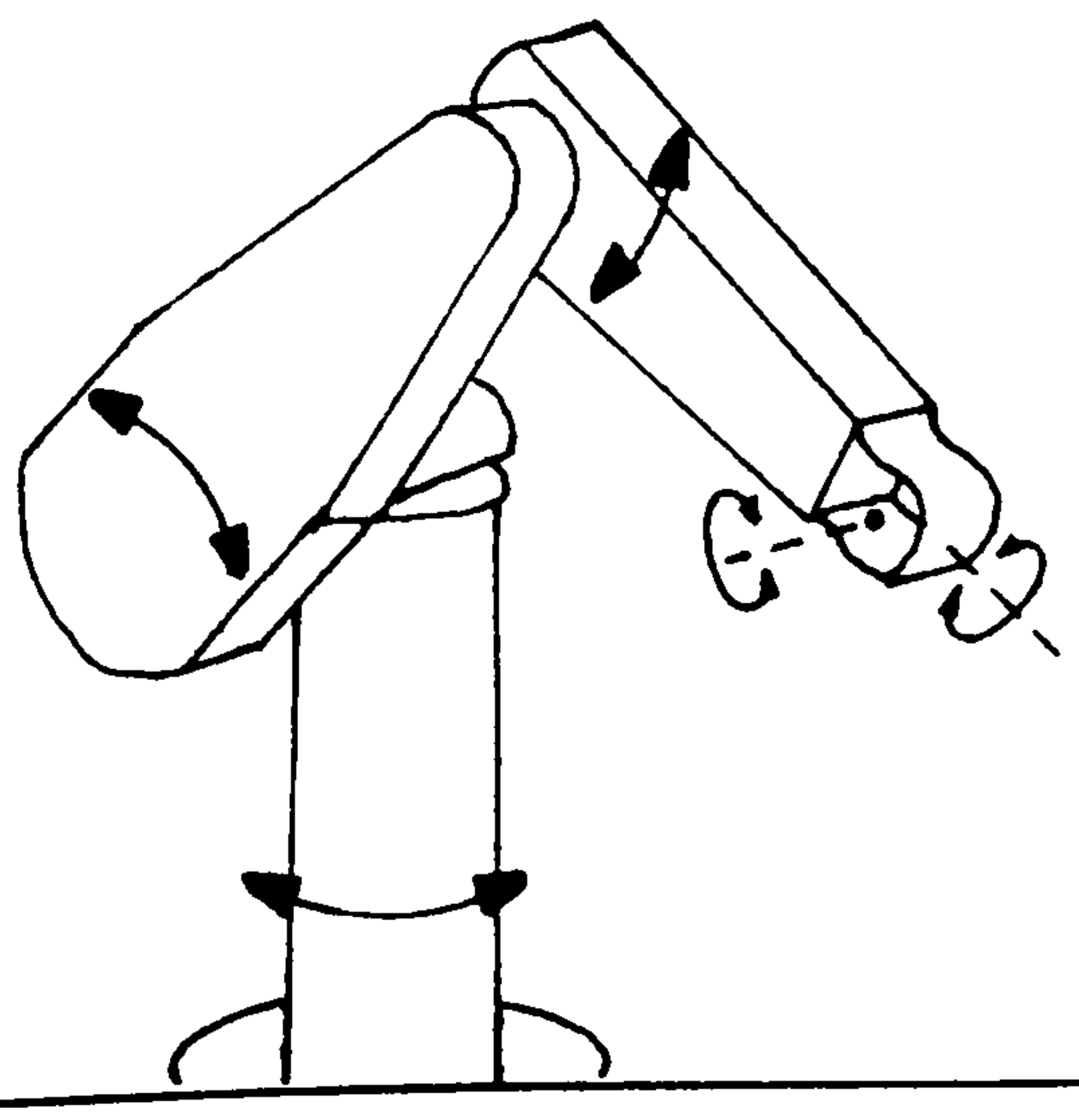
b) cylindrical coordinate



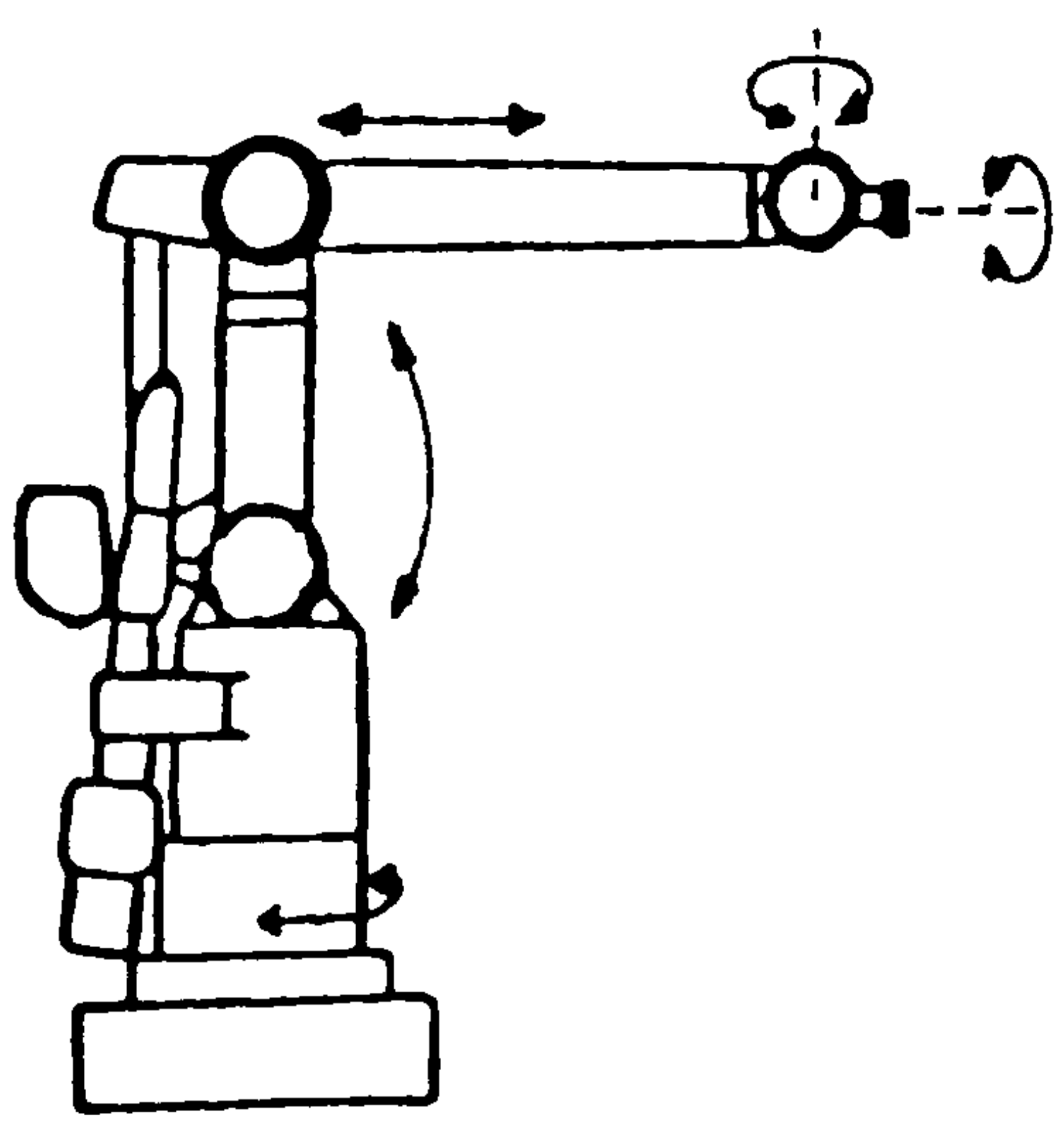
c) spherical



di) Jointed spherical



dii) Jointed parallelogram



3.1.1 Cartesian coordinate

This is the simplest type as it contains only linear joints which move in straight lines parallel to cartesian coordinates (X, Y, Z). Thus, it is also referred to as a rectangular type robot. The arm can move in and out and sideways in the horizontal plane and up and down in the vertical plane (see Figure 3.1a).

There are two types of rectangular designs; Sliding type (mounted on a sliding floor) or gantry-type (mounted above the work on a gantry frame).

3.1.2 Cylindrical coordinate

This type comprises a horizontal arm mounted on a vertical column, which is itself mounted on a rotary base (see Figure 3.1b). The arm is a linear joint which can move in and out from the base to extend or retract. The arm carriage is also a linear joint which moves up and down on the column and these two joints can be rotated about the column by the rotary joint on the base.

3.1.3. Spherical

This type has one linear and two rotary motions (see Figure 3.1c). The arm can move up and down at its rotary joint which is mounted on a cylinder at the base. The arm is rotated about the cylinder by a rotary joint.

3.1.4 Articulated arm

This is the most sophisticated type and is the one which most resembles a human arm. Thus, it is also known as an anthropomorphic or jointed-arm type. There are two main types of jointed arm robots (Klafter et al,1989);

3.1.4.1 Jointed Spherical

This type of robot consists of three major rotary joints acting as the waist, the shoulder, which is mounted on the waist, and the elbow which is mounted at the end of the shoulder link (see Figure 3.1di).

The range of rotation on each joint enables the robot gripper to reach many more points in space than with other robot configurations.

3.1.4.2 Jointed Parallelogram

This type is similar to the jointed spherical robot except that the single rigid member upper arm is replaced by a multiple close-linkage arrangement in the form of a parallelogram (see Figure 3.1dii).

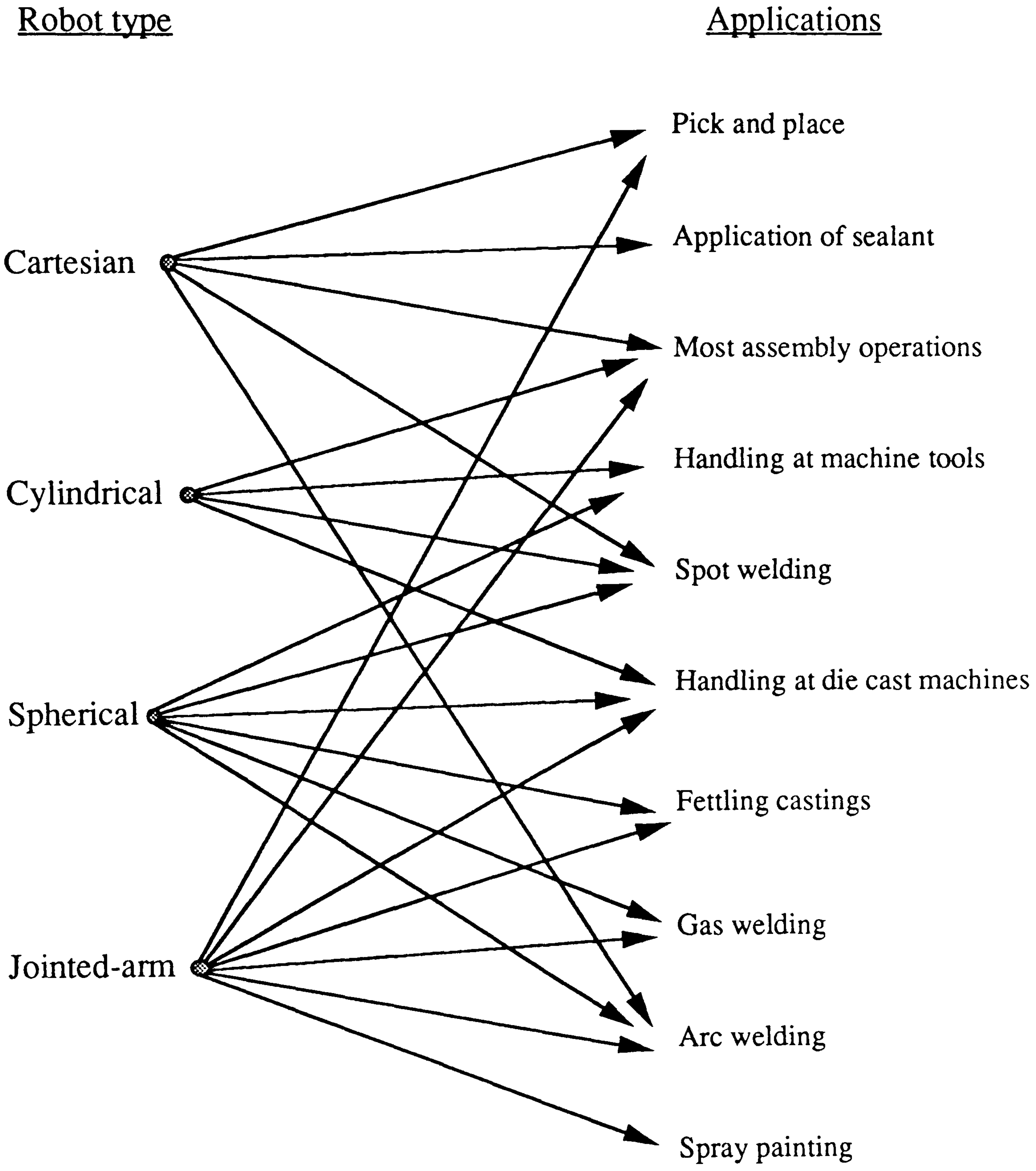
The major advantage of this design is that it can handle a larger load capacity than a jointed spherical robot of the same size. This is because the weight of the arm itself is reduced as the joint actuators are located near the base of the robot instead of at the joint.

The disadvantage of this design is that its work area is more restricted than the jointed spherical type as it cannot 'flip' joints 2 and 3 over-the-top of the base (see section 3.3).

The different types of movement capabilities that are produced by these different designs mean that it is important to select the correct type of robot for the intended application. Figure 3.2 shows the range of applications to which each robot configuration type is most suited (adapted from Hartley, 1983, p.21). It can be seen that there is a great deal of overlap between robot types in the range of applications to which they are suited, but that the jointed arm type is slightly more versatile than the other types. In 1985, just over half of the robots sold in the USA were of the articulated design (53%), 21% were cartesian, 16% cylindrical and 10% spherical. This distribution is forecast to remain unchanged in the foreseeable future (SME, 1985). Selecting the right type of robot is becoming increasingly a complex decision. In 1978 there were 24 commercial robots to choose from, whereas in 1983 there were at least 280 models available (Towill, 1984).

As has been shown, the major axes of a manipulator define the configuration of the robot and the range of movements it is capable of. This also affects the work area within which an object held by the robot may be positioned. Thus, the first three degrees of freedom of a robot define how it may be used to position its end effector. However, robots are not normally

Figure 3.2 Suitable industrial applications for each robot type



Adapted from: Hartley (1983)

limited to only three degrees of freedom, they usually have five or six. The last three degrees of freedom are located on the wrist which is attached to the end of the arm. An end effector, suitable for the desired task (e.g. welding gun, gripper for manipulation, tool, etc) would then be attached to the wrist. The wrist may comprise up to three rotary joints which are used to control the orientation of the end effector with respect to the workpiece. These motions are described as;

i) wrist pitch. This refers to a rotary motion of the wrist about a horizontal axis passing through the arm (see Figure 3.3a).

ii) wrist yaw. This refers to a rotary motion of the wrist about a vertical axis passing through the arm (see Figure 3.3b).

iii) wrist roll. This refers to a rotary motion about the axis of the link (see Figure 3.3c).

3.2 Robot movement

The degrees of freedom of robot motion have been defined as the number of independent JOINT movements that a robot is capable of. However, with several robot configuration types the range of movements available is increased by switching to another mode of programming. There are three modes of programming available, although not all robot systems use all of them. The terms given below are those used for the Unimate robot system. Other robot systems use different terms for these programming modes (e.g. hand, cylindrical) although they are essentially the same.

3.2.1 JOINT mode

Joint mode of programming refers to the independent motions produced by each individual joint described in section 3.1. Each joint can move in two directions; clockwise/anticlockwise for a rotary joint and in/out for a linear joint (see Figure 3.4). The jointed-arm robot has all rotary joints whereas a cylindrical type robot has a rotary/linear combination. By moving each joint appropriately, the tool can be positioned and oriented as desired at any point within the robot work area.

Figure 3.3 Robot wrist motions

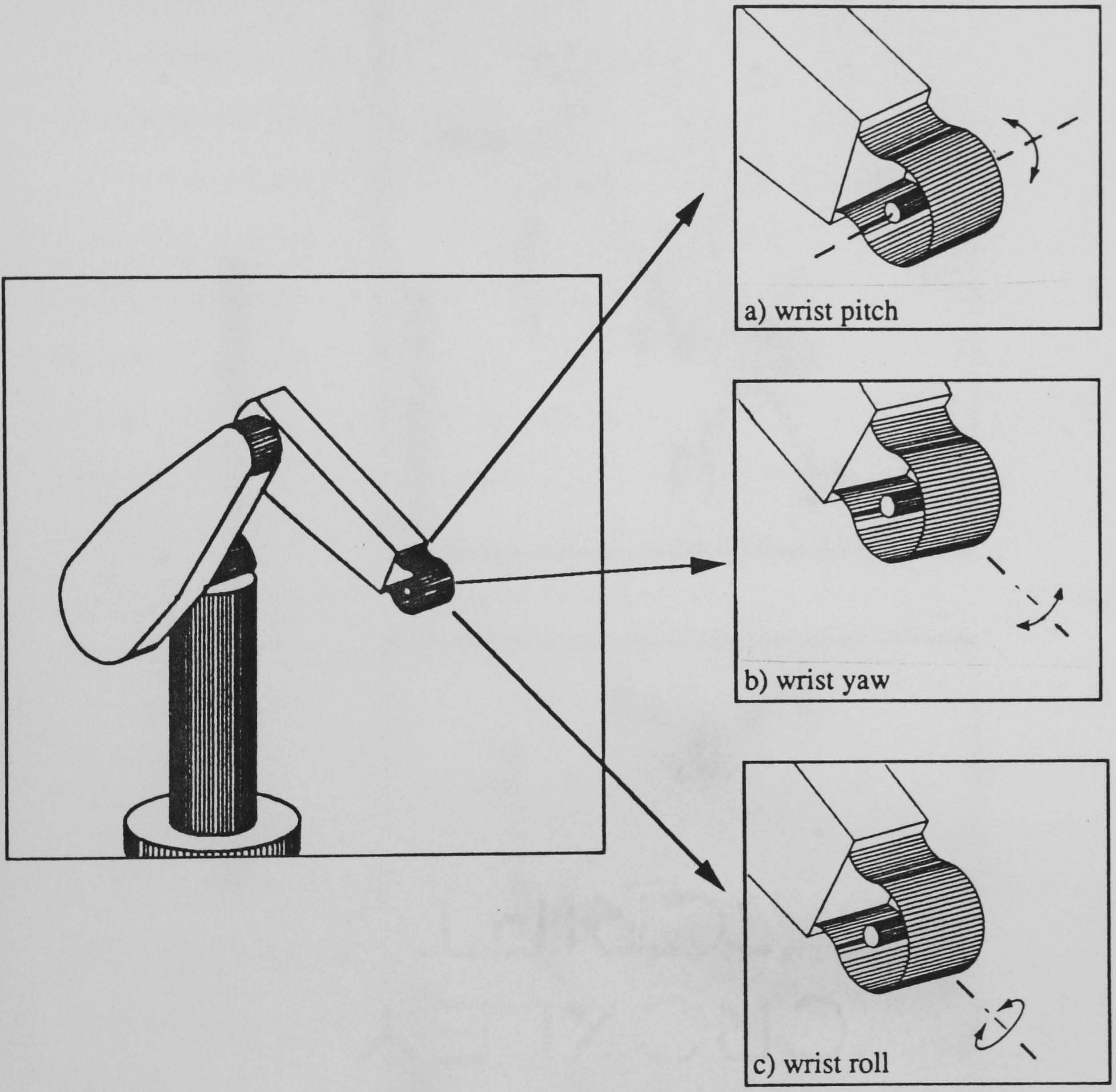
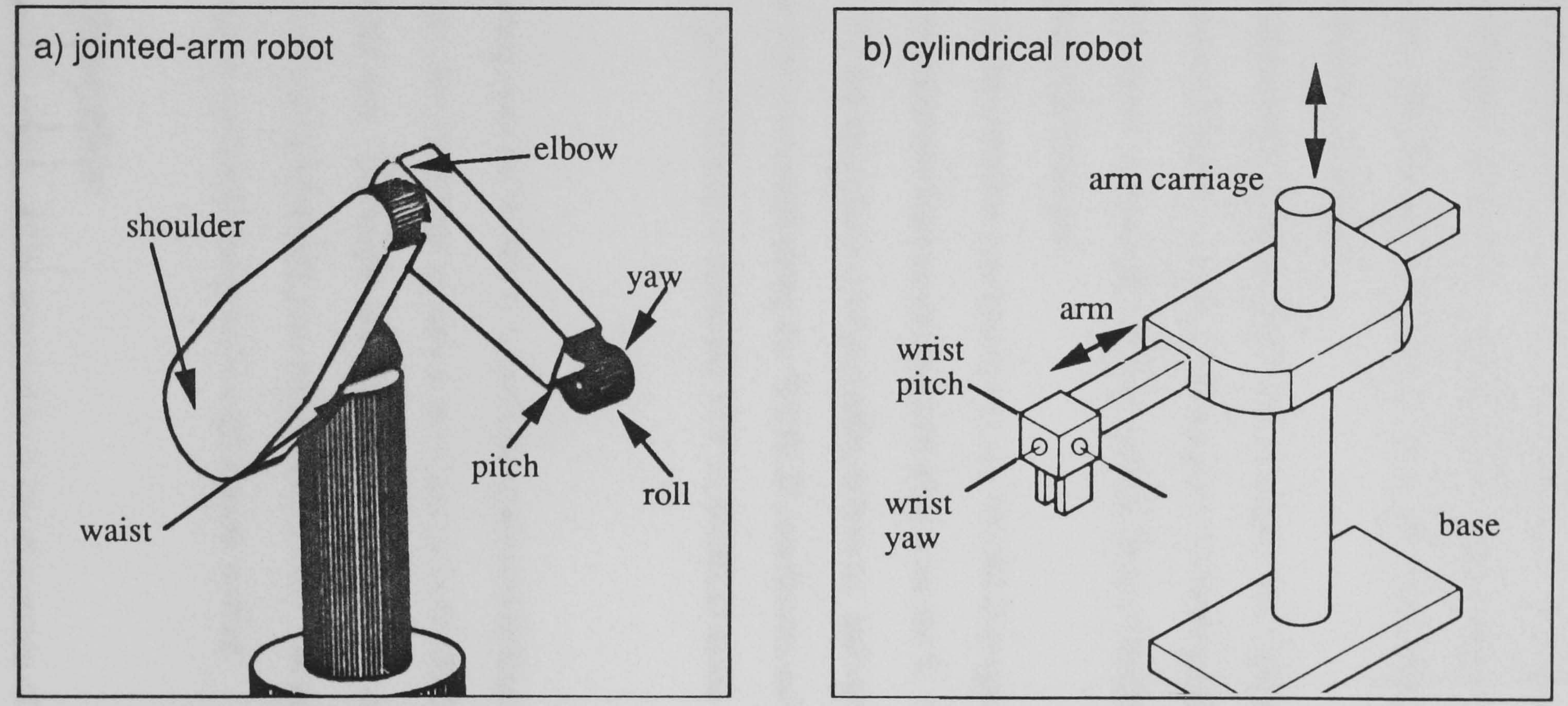


Figure 3.4 Robot movement in joint mode



a) jointed-arm robot

b) cylindrical robot

3.2.2 WORLD mode

The world coordinate system is fixed, with its origin at the centre of the robot base. When controlling an articulated type robot in WORLD mode, it is the Tool Centre Point (TCP) which is moved along straight lines parallel to the X, Y, Z coordinate axes (see Figure 3.5a). There are still up to six degrees of freedom within this mode; three for positioning the tool and three for controlling tool orientation. RX, RY and RZ motions rotate the TCP around the appropriate coordinate axis for tool orientation.

The advantage of this programming mode is that it enables faster and more accurate tool positioning within the coordinate planes of motion. For example, if the programmed task involves palletising, it is much easier to move the TCP in straight lines vertically and horizontally than moving each individual joint.

For some robot types (e.g. the cartesian configuration), the WORLD programming mode is the only one available since its joint movements are in accordance with the X, Y, Z coordinates (Figure 3.5b). For the articulated configuration, however, individual joint movements do not correspond to movement along the WORLD coordinates and several joint movements would be used simultaneously to move the TCP in WORLD mode.

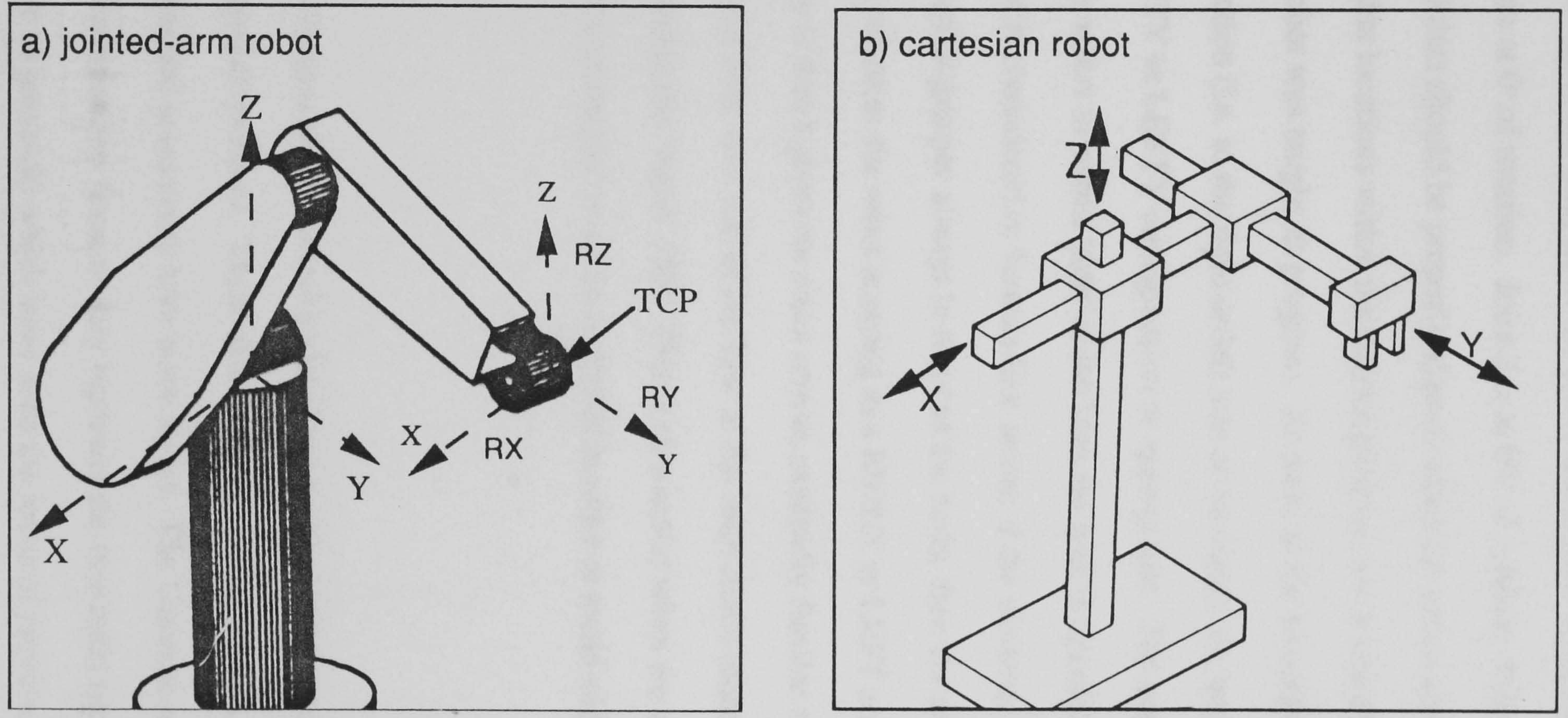
3.2.3 TOOL mode

Tool mode of programming uses the WORLD coordinate system to define motions (e.g. X, Y, Z, RX, RY, RZ). However, the coordinate system is not fixed as in WORLD mode but is relative to the orientation of the tool. The origin of the coordinates is fixed at the TCP and therefore rotates and swivels in accordance with movements of the tool. The advantage of this system is that it enables accurate tool positioning at an angled work surface.

3.3 Robot arm-configuration

The robot arm-configuration, which will be returned to in the discussion of the robot motion control task (chapter 4), refers to the relative orientation of the links of the arm at a given moment. It is a feature of the jointed spherical type of articulated robots only and is produced by the robots' ability to 'flip' the shoulder and elbow joints to one side of the robot

Figure 3.5 Robot movement in world mode


a) jointed-arm robot

b) cartesian robot

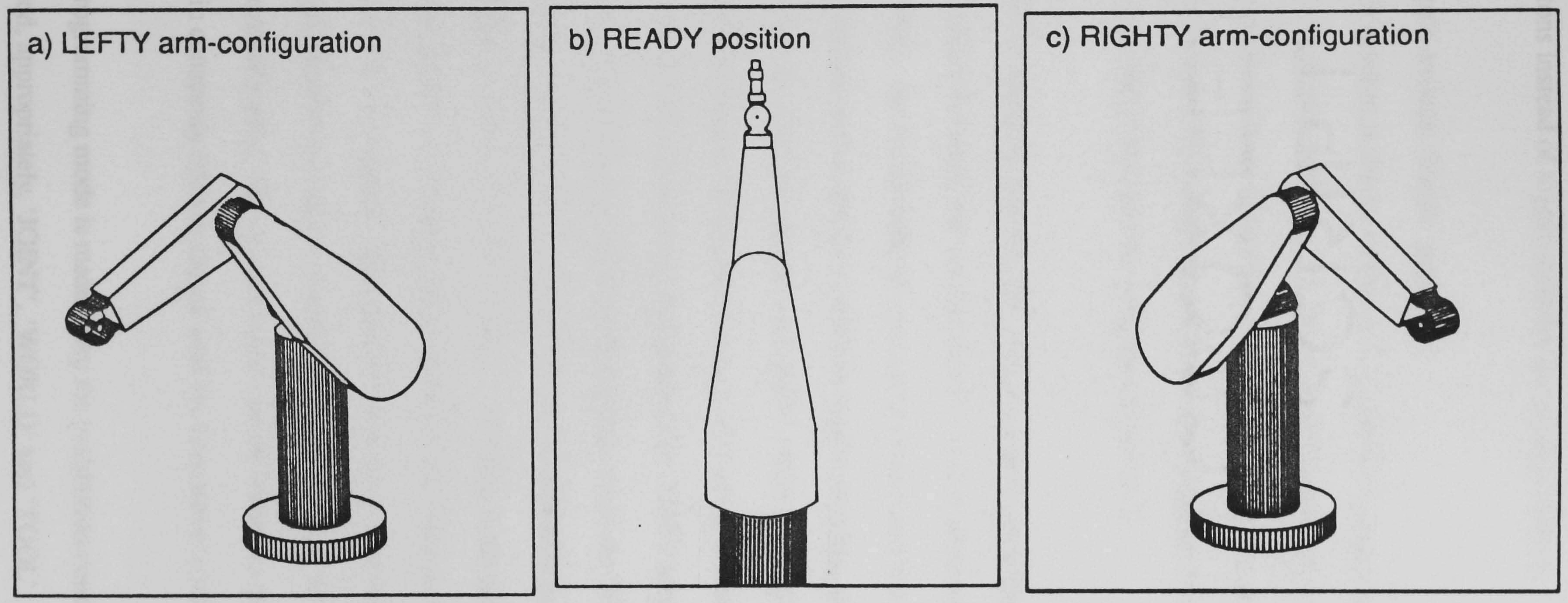
base. This is more clearly demonstrated diagrammatically (see Figure 3.6). The Unimate PUMA robot is shown in its 'READY' position (Figure 3.6b), in a 'RIGHTY' arm configuration (Figure 3.6c), and in a 'LEFTY' arm configuration (Figure 3.6a). The READY position is the 'home' position of the robot arm; all of the joints are aligned vertically and all but joint 2 (the shoulder joint) are at 0° of rotation. Joint 2 is at 90° of rotation. When the robot is initially calibrated, all of the joints should be properly aligned when the arm is moved to the READY position, this ensures that locations within the control program are at exactly the same position in space as when the robot was taught its program. As soon as the shoulder joint (joint 2) is moved in either direction (i.e. to the right or left side of the base), the arm can be described as being in the RIGHTY or LEFTY configuration as appropriate. The arm configuration, therefore, simply refers to which 'side' of the base the arm is operating. This may be more readily understood if considered in 'human-like' terms; if the observer imagines 'himself as the robot', with the robot gripper always in front of the body, then the arm configuration can be defined by whether the robot is acting as a RIGHT or LEFT arm.

The advantage of this facility is that it gives the robot arm an extremely flexible range of movement and it can move the tool from one side of the base to the other much more quickly by going 'over-the-top' than rotating the 'waist' 180°. This is also useful when the operating space is limited and the robot movement path must be restricted in order to avoid collision with fixtures and other machinery.

3.4 Teach controls

Two different teach pendant designs are described in detail below; the Unimate toggle-switch pendant and the ASEA joystick pendant. These two designs are described in detail because they are used for experimental assessment later in the thesis. The Unimate and ASEA teach pendants were chosen for examination because they represent the two main types of motion control design (i.e. button vs joystick) which have been the focus of previous experimental work (described in section 2.2.3). Moreover, these teach pendants were more readily available to the author than other types. It should be noted however, that the Unimate teach pendant is an older version than that used by other experimenters. The layout and

Figure 3.6 Arm-configurations of the jointed-spherical robot



a) LEFTY arm-configuration

b) READY position

c) RIGHTY arm-configuration

labelling of the two versions is identical but the main difference is that the newer version uses microswitch pushbuttons instead of toggle-switches for motion control.

3.4.1 Unimate toggle-switch teach pendant

The Unimate teach pendant is shown in Figure 3.7, and can be used to control a jointed-spherical type of robot as shown in Figure 3.8. Teach control is performed via a computer terminal linked to the robot computer-controller. A programming language called 'VAL' is used which was derived from the BASIC computer programming language (Gruver et al, 1983).

This type of teach pendant is not used for program control at all.

Referring to Figure 3.7 it can be seen that the motion controls are grouped according to function; on the right side of the teach box are the controls used to physically drive the robot degrees of freedom (DOF). On the left side are the controls that select the programming mode.

The controls for robot movement are three-position toggle-switches, spring-loaded to the centre position. There are six switches, one for each DOF, which are dual-labelled in accordance with the different types of robot movement in each programming mode. The numbers 1 to 6 represent the individual joints controlled under JOINT mode. X, Y, Z, RX, RY and RZ represent the coordinate axes of movement along which the TCP is moved under WORLD and TOOL programming modes. Each DOF can be moved in both a positive and negative direction and this is indicated by the '+' and '-' labelling at the sides of these switches. When a toggle switch is moved in either direction, the robot arm or TCP will move appropriately until the switch is released. Also grouped with these switches is the gripper control. This is also a three-position toggle-switch and is used to open 'O' or close 'C' the gripper attached to the robot's wrist. This switch is also spring-loaded to the centre although the gripper will remain constantly open or closed until the alternative is selected.

Selection of the programming mode is made using the pushbutton controls on the left side of the teach box marked, appropriately, 'JOINT', 'WORLD' and 'TOOL'. When a button is selected, the red light adjacent to it is illuminated. This indicates that it is the current status of

Figure 3.7 Unimate toggle-switch teach pendant

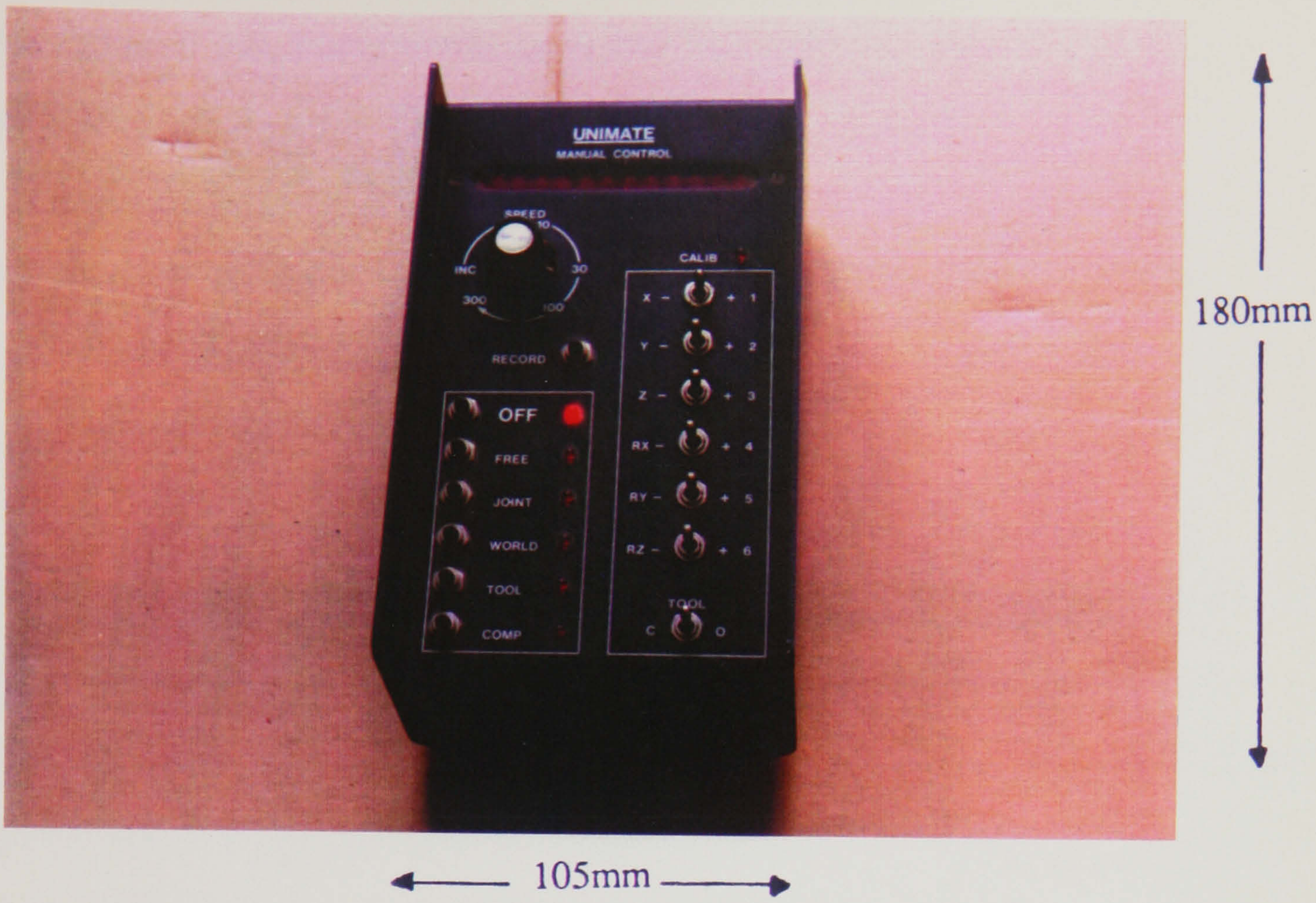


Figure 3.8 PUMA 560 jointed-spherical robot

the teach control system and will remain so until an alternative is selected. The other pushbuttons grouped with these controls are as follows; 'OFF' immediately stops the robot if test running through a program. 'FREE', when selected in association with one of the joint controls, releases the servo control brake from that joint so that it can be pushed by hand. This is useful when the robot arm is 'stuck' in a position from which it cannot be driven using the motion controls. 'COMP' places the control of the robot to the computer terminal whereupon it will not respond to any of the motion controls.

During motion control, the speed of robot movement can be altered by adjusting the speed selector knob at the top left of the teach pendant. Clockwise rotation of the knob increases speed up to a maximum of 0.25m/s. Conversely, anticlockwise rotation will reduce the speed. At the slowest end of the scale, movement is in small increments (1 mm/s).

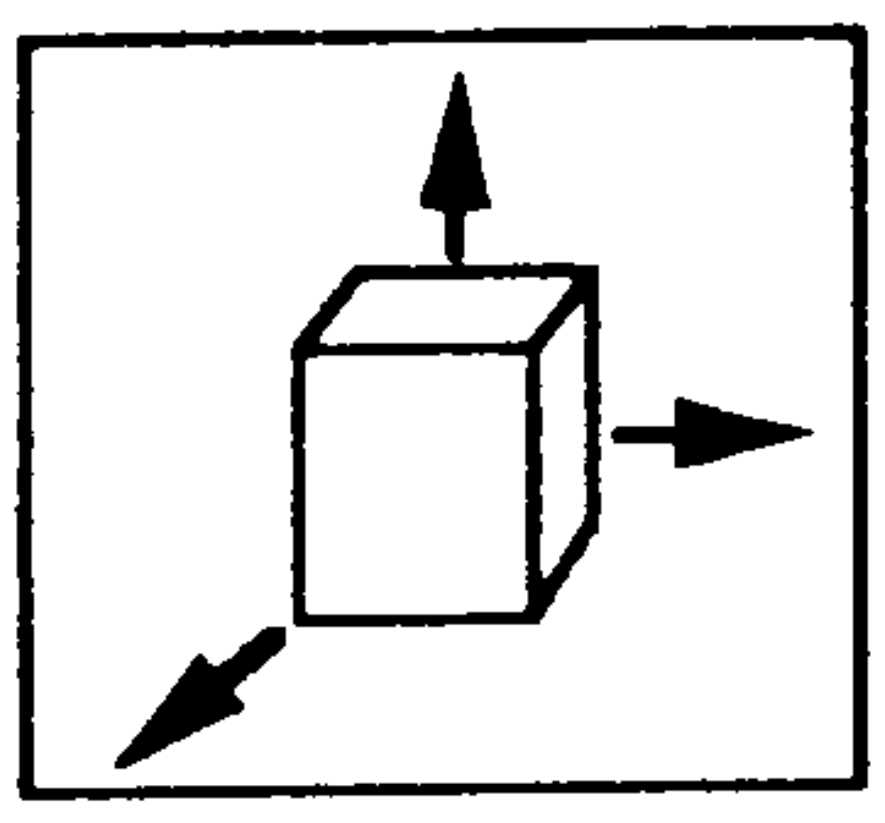
The other control on the teach pendant is the 'RECORD' button which is used to register the current configuration of the robot arm to the computer software. The coordinate location of the TCP and status of the gripper are recorded and assigned a location number. When, during operation of the program, the arm is instructed to move to that location number, the TCP will be moved to the exact location recorded. It is important to remember, however, that the path of motion taken by the robot to get to each location is not necessarily the same as that used by the programmer in teaching these locations, since only the final position is recorded.

There are two displays on the teach pendant; the 'CALIB' indicator is illuminated when, after initial start-up, the robot arm has not been calibrated and warns the programmer that this must be done before operating the robot. The LED display panel has a single line of characters that can show 23 messages. These state the mode of control that the robot is running under (teach pendant, computer or normal operation), or indicate when the limit of travel on a particular joint has been reached, or display error messages.

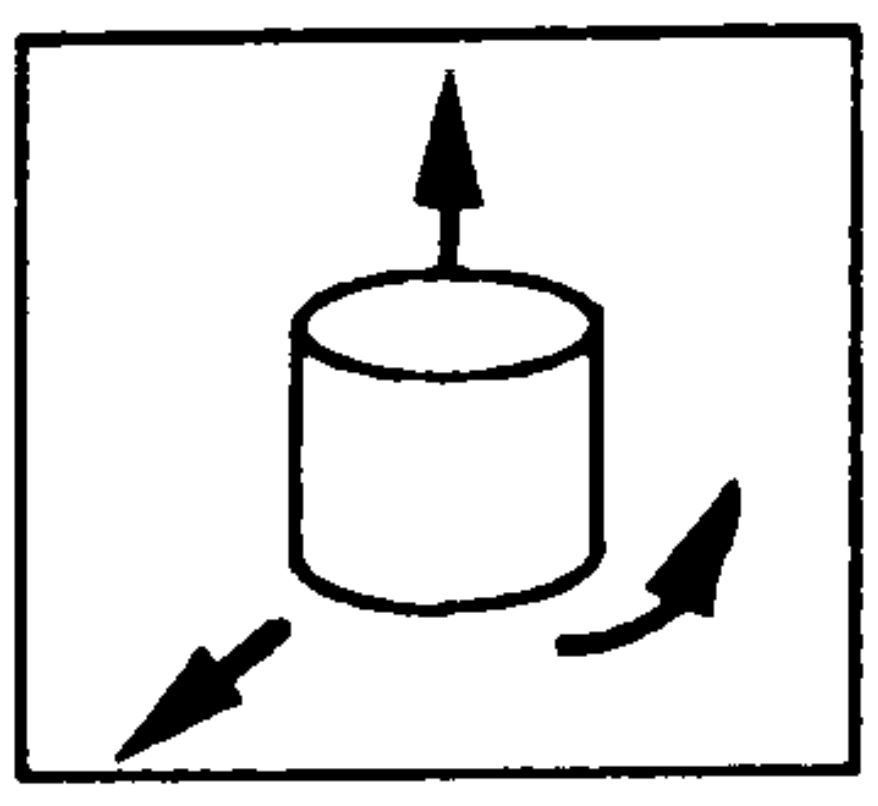
3.4.2 ASEA joystick teach pendant

The ASEA teach pendant is shown in Figure 3.9, and can be used to control a jointed-spherical type of robot as shown in Figure 3.10. However, due to differences in communication systems, it cannot be used to operate the PUMA robot shown in Figure 3.8, nor can the Unimate teach pendant operate the ASEA robot. The ASEA teach pendant is used both for motion control and program control and is therefore more complex in design than the Unimate teach pendant.

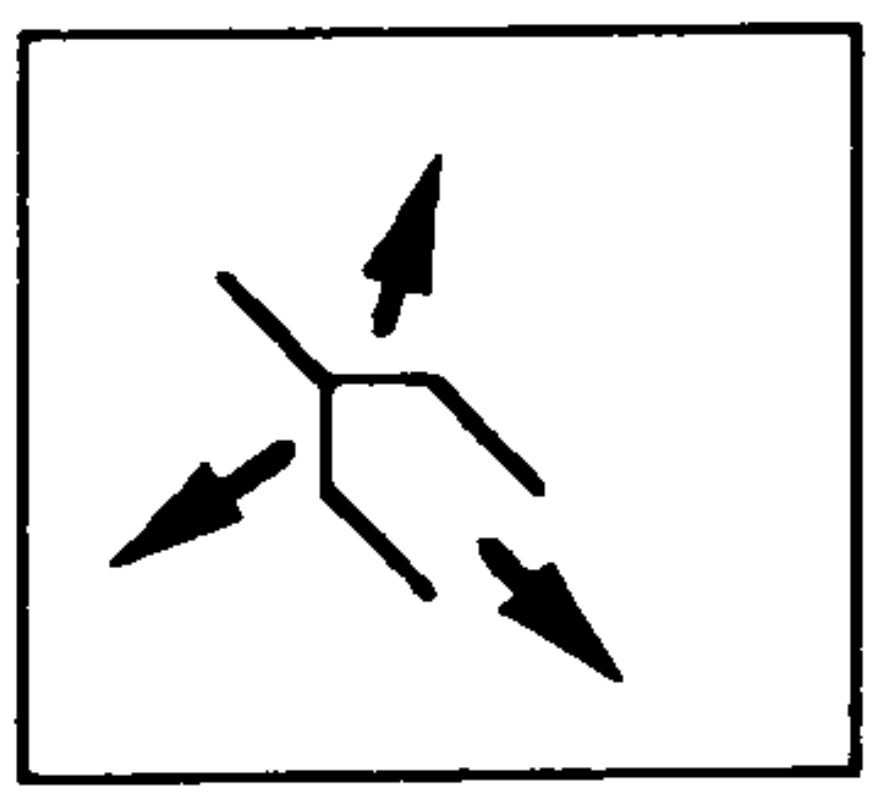
With reference to Figure 3.9, motion control is achieved using the 3-axis joystick situated at the top right side of the teach pendant. The three axes of movement on the joystick (left-right, forward-back and clockwise-anticlockwise rotation) correspond to three of the DOF in which the robot can be moved. These may be either the three major DOF, governing the positioning of the TCP, or the three minor DOF, relating to the orientation of the tool. Joystick control is switched between the two sets of DOF by a two-position toggle-switch next to the joystick. Selection of the mode of programming for motion control (JOINT, WORLD or TOOL) is made by pressing one of the three buttons located at the top of the centre group of buttons on the teach pendant. The mode selected is indicated by the illumination of a yellow light in the top left corner of the appropriate button. The labelling of these buttons is symbolic as shown below;



= WORLD mode



= JOINT mode



= TOOL mode

Figure 3.9 ASEA joystick teach pendant

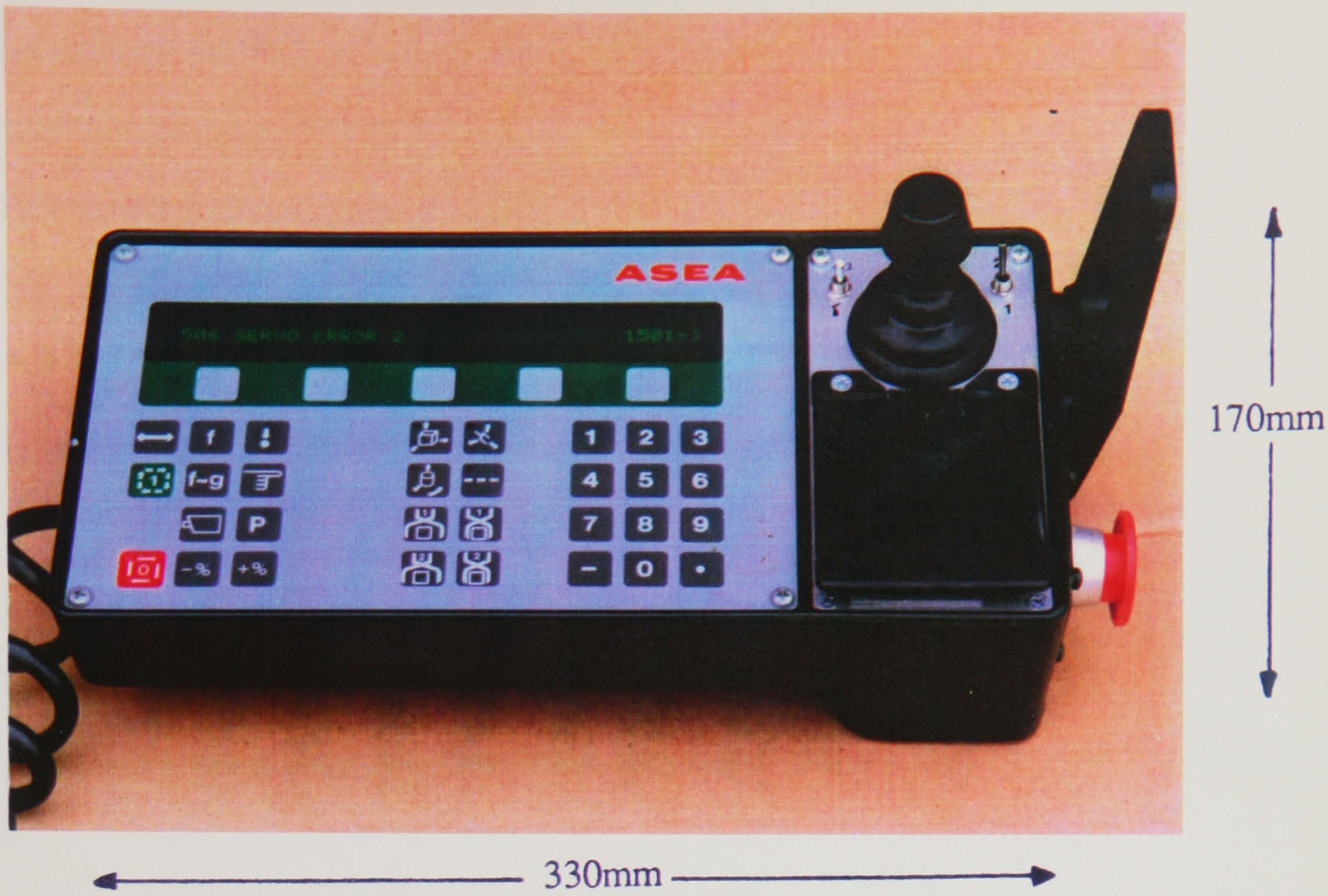
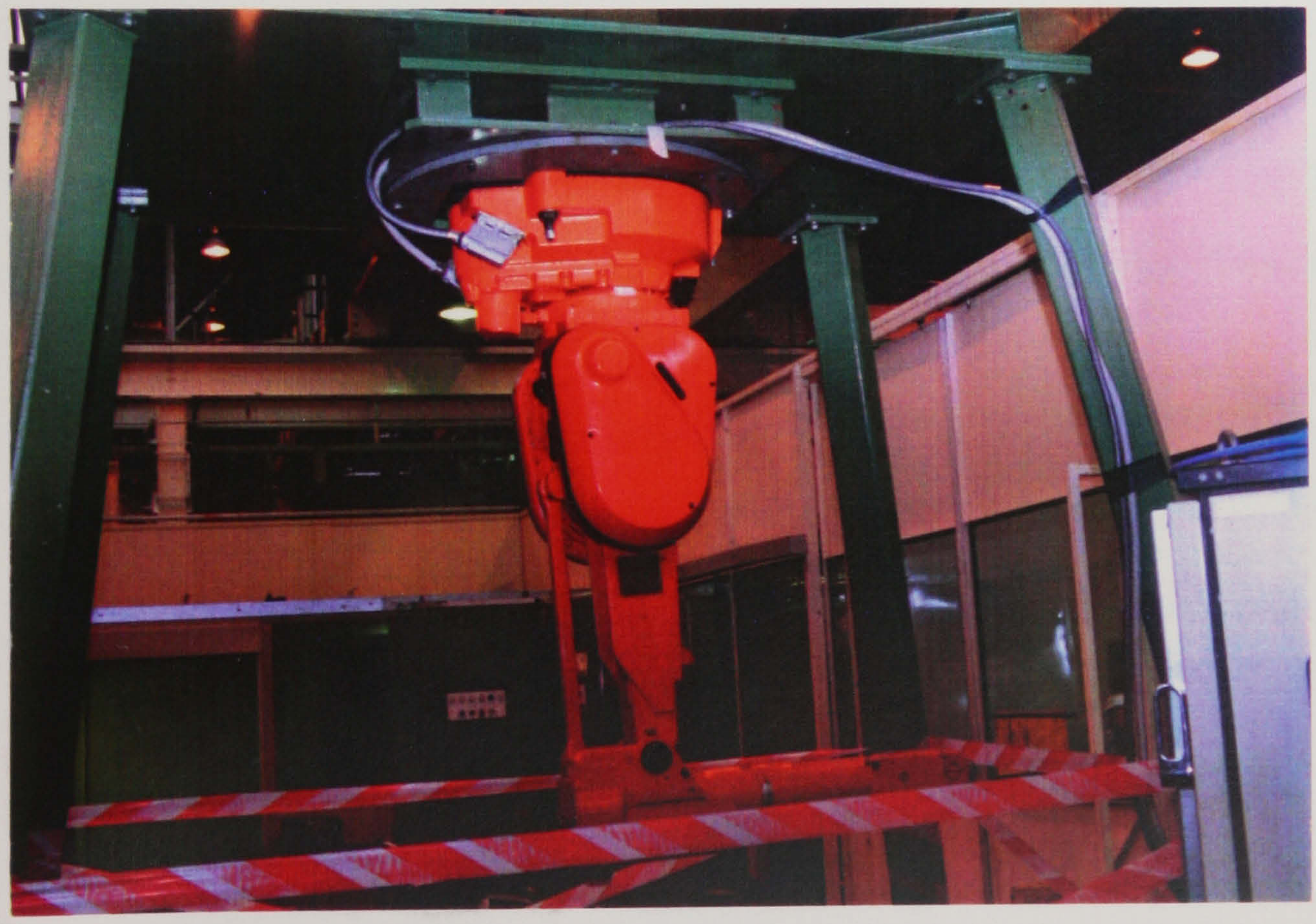


Figure 3.10 ASEA IRB 2000 jointed-spherical robot (gantry mounted)



The number of different types of robot movement controlled by each axis on the joystick are too numerous for clear labelling. Therefore the joystick has no labelling at all and so the programmer must remember which axis is relevant to each DOF and which direction of movement of the joystick produces positive and negative movement of the robot.
Speed of robot motion is regulated by the degree of deviation of the joystick control and is logarithmically proportional. Thus, the further the joystick is moved in any direction, the faster is the corresponding robot movement. Robot motion is activated only when the safety pad below the joystick is held down. Thus, the programmer must rest his/her wrist on the safety pad continously while moving the joystick. Incremental motion is achieved independently by pressing the button marked - - - and the robot will continue at this speed until the button is de-selected. The four buttons at the bottom of this group are for opening and closing the robot gripper.

The rest of the controls on the teach pendant are used for creating the control program. This operation, as well as location recording, is achieved by pressing the appropriate function key on the left side of the teach pendant and then working through the menu options displayed on the lower line of the 2-line LED display. The five unlabelled buttons directly beneath the display are used to select the desired option in the menu. Thus, a series of up to five options are presented at each level of the menu and the programmer works through these until the program instruction is completed.

The two coloured buttons on the teach pendant control the initiation of automatic program running (green) and immediate stop of program running (red). There is also an emergency stop button on the side of the teach pendant which immediately removes motive power from the robot arm.

3.5 Control-motion relationship

The effect of the variation in control design between these two teach pendants will now be examined. For two different programming modes (JOINT and WORLD), the control-motion relationship for individual robot moves will be compared for each control design. It should be noted that these control-motion relationships are those applied by Creed (1987) who stated that; "Teach pendants are designed to be used from the front of the robot." (p.2). Unfortunately, during the course of the research work presented in this thesis, it was discovered that Creed's statement was not correct. In actual fact, the Unimate and ASEA teach controls are designed to be used from different orientations to their robots. This will be described later in section 5.3.4. Although the diagrams are labelled in accordance with Creed's assumptions and not derived from the actual teach pendants, they do allow valid comparison of the two types of teach pendant when used in the same situation.

3.5.1 JOINT mode

In Figure 3.11, three different joint movements of a jointed-spherical type robot are shown together with the appropriate control that would be used to achieve each movement using either teach pendant. On the basis of Creed's (1987) assumptions described above the robot is represented as viewed from the front and in its RIGHTY configuration.

Joint 1

It can be seen that a movement of joint 1 in the positive direction will rotate the robot 'waist' to the right (Figure 3.11a). To achieve this move, the top toggle-switch on the Unimate pendant is moved to the right (labelled +1), and the ASEA joystick is moved to the right.

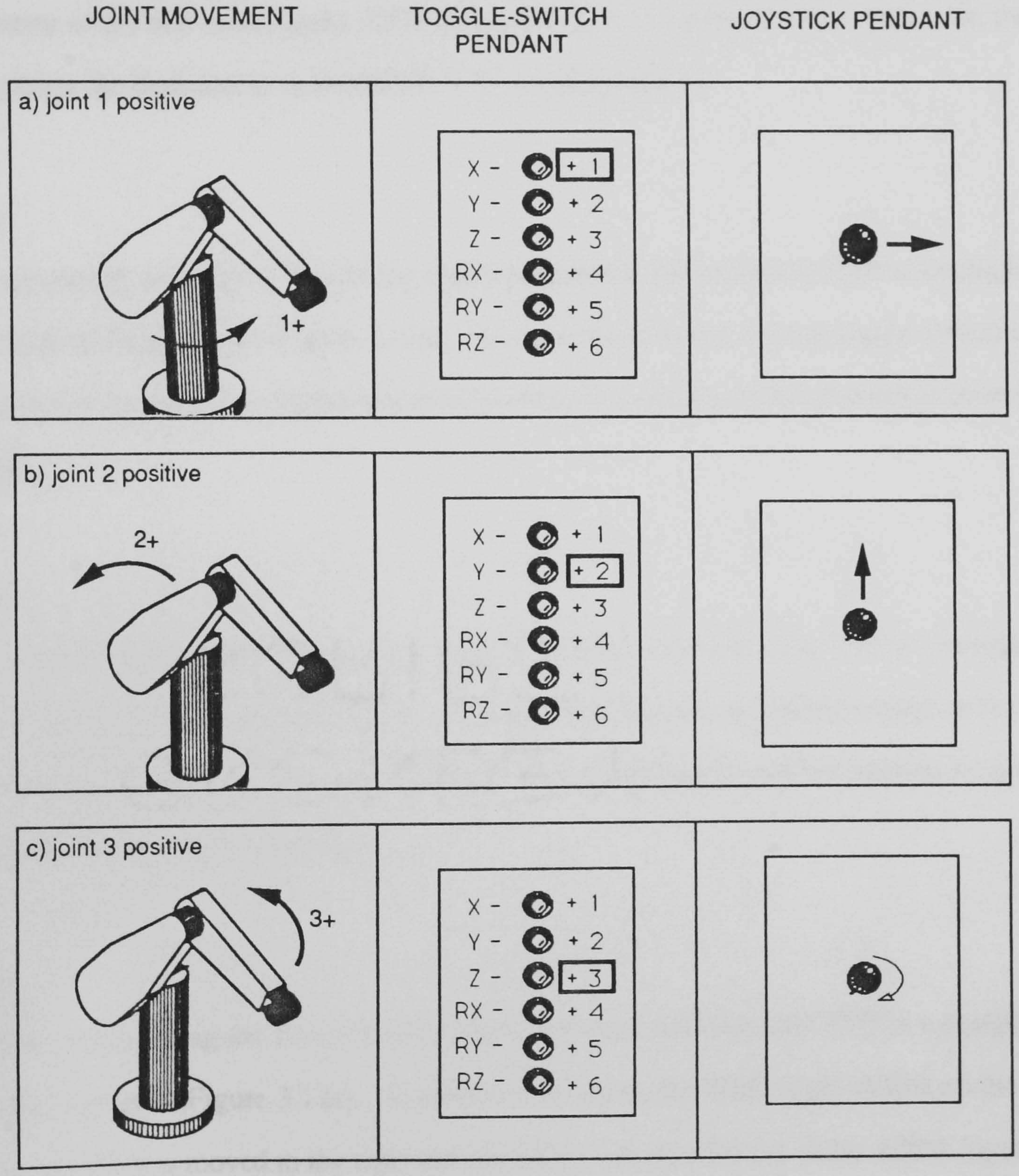
Joint 2

A movement of joint 2 in the positive direction will rotate the robot 'shoulder' upwards (Figure 3.11b). To achieve this move, the second toggle-switch on the Unimate pendant is moved to the right (labelled +2), and the ASEA joystick is moved forwards (away from the operator).

Joint 3

A movement of joint 3 in the positive direction will rotate the robot 'elbow' upwards (Figure 3.11c). To achieve this move, the third toggle-switch on the Unimate teach pendant is

Figure 3.11 Control-motion relationships for the Unimate and ASEA teach pendants when controlling robot motion in joint mode



moved to the right (labelled +3), and the top of the ASEA joystick is rotated clockwise, converse to the direction of movement of the robot joint.

3.5.2 WORLD mode

In Figure 3.12, the jointed spherical type robot is represented as showing three different movements of the tool centre point (TCP) along the X,Y,Z coordinate axes. Again, the robot is viewed from the front and is in its RIGHTY arm configuration.

X axis

A movement along the X axis in the negative direction will move the TCP in a straight line to the right of the observer (Figure 3.12a). To achieve this move, the top toggle-switch on the Unimate teach pendant is moved to the left (labelled X-), and the ASEA joystick is moved to the right.

Y axis

A movement along the Y axis in the negative direction will move the TCP in a straight line away from the observer (Figure 3.12b). To achieve this move, the second toggle-switch on the Unimate pendant is moved to the left (labelled Y-), whereas the ASEA joystick is moved forwards (away from the operator).

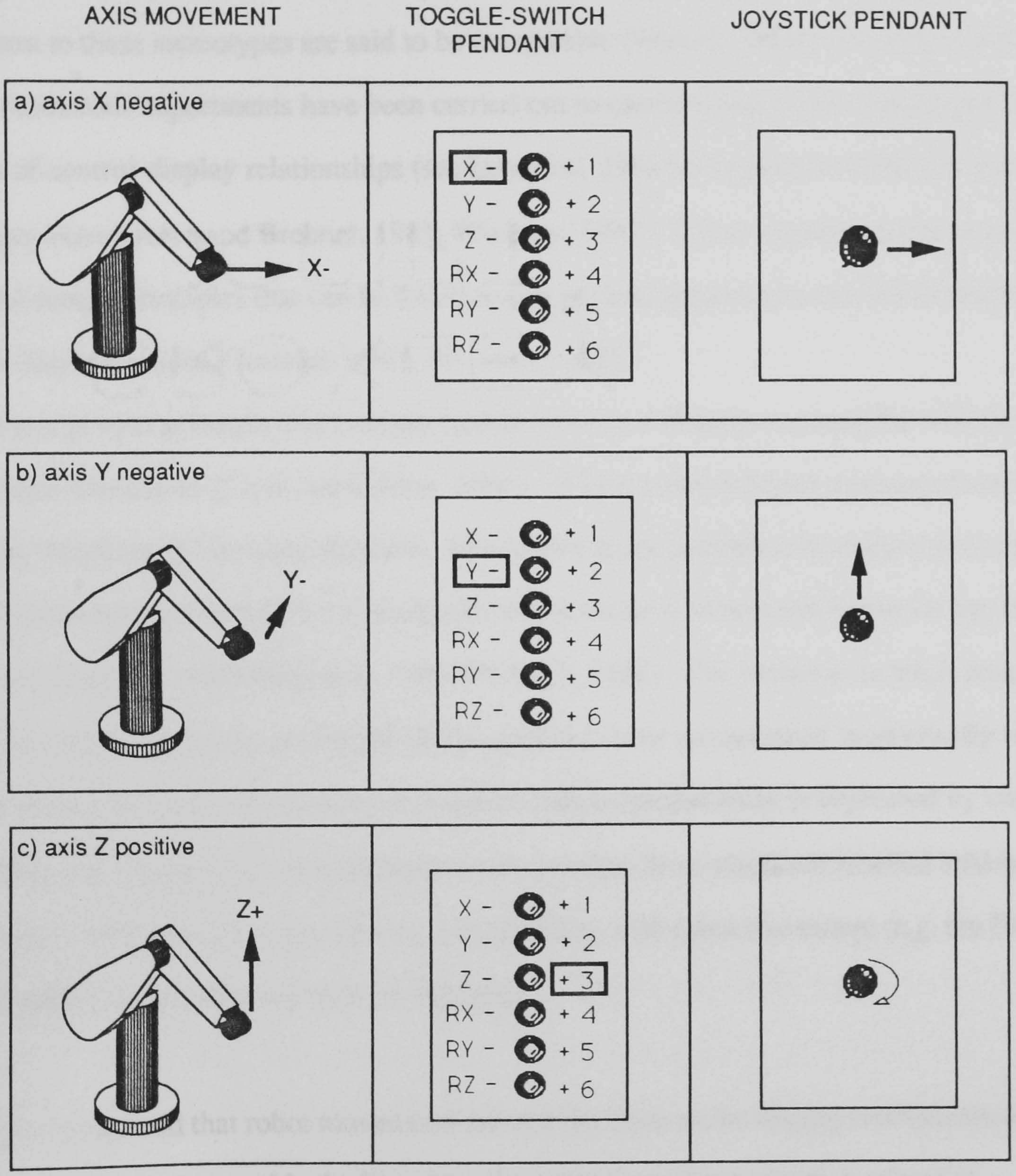
Z axis

A movement along the Z axis in the positive direction will move the TCP in a straight line vertically upwards (Figure 3.12c). To achieve this move, the third toggle-switch on the Unimate pendant is moved to the right (labelled Z+), whereas the top of the ASEA joystick is rotated clockwise.

3.5.3 Control-motion compatibility

Control-motion compatibility is one of the issues examined in some detail in the experimental work described later. At this point, however, it is useful to discuss the

Figure 3.12 Control-motion relationships for the Unimate and ASEA teach pendants when controlling robot motion in world mode



control-motion compatibility of the two teach controls described above in order to provide the reader with an indication of the problems of non-standardised controls.

Control-motion compatibility is achieved when a given control movement produces either an expected effect or an expected movement in its associated display. The expectations of the majority of the population are called population stereotypes and control movements which conform to these stereotypes are said to be compatible (Murrell, 1965). Over the last forty years numerous experiments have been carried out to measure population stereotypes for a range of control-display relationships (see Loveless, 1962 for an early review; and more recently Petropoulos and Brebner, 1981; Wickens, 1987). These experiments have produced control design principles that can be found in any general ergonomics text books (Murrell, 1965; Sanders and McCormick, 1987; Wickens 1984).

It is a general principle that controls should move in a direction compatible with the display or system movement (Clark and Corlett, 1984). Where possible linear motions of control and display should be in the same direction. Where this is not possible it is acceptable to move a lever up for forward and right for clockwise and to rotate a control clockwise for up, right or forward (Morgan, 1963; Pheasant, 1986; Wickens, 1987). The variation in teach pendant designs could cause some ambiguity on this point as some are designed to physically resemble robot movement (e.g. the joystick) whereas on others compatibility is expressed by control labelling (e.g. on the Cincinnati Milacron teach pendant the controls are labelled left/right and up/down). Other designs may have no compatibility with robot movement (e.g. the Unimate pushbutton pendant labelled with +/- legends).

It is recognised that robot movements are not the same as the display movements defined in most experiments reported in the literature; the robot is an object which is moved in 3-dimensions, not a 2-dimensional display. However, it is considered that certain principles may still apply but there is very little literature available which is relevant to this specific situation. As the present situation does not refer to the control of a display, the term 'control-motion' has been used to associate activation of a control on the teach pendant with the resulting movement of the robot arm, and thus control-motion compatibility is a more suitable term than control-display compatibility.

For joint mode programming, it could be argued that the toggle-switch pendant may be easier to use as the control-motion relationship is logical and consistent: the positive controls are all on the right side of the switches and correspond to robot joint movements to the right or upwards. The joystick control, however, whilst maintaining a logical control-motion relationship with all positive joint movements relating to a movement of the joystick to the right, forwards or clockwise, may cause confusion for the operator when the direction of joint motion is not the same as the direction of joystick movement (e.g. joint 3). Whereas for world mode programming, it could be argued that the joystick pendant may be simpler to use, particularly for controlling movement along the X and Y axes, as joystick movement corresponds directly to the direction of robot motion.

The particular problems that programmers or operators may have in understanding the relationship between the controls and robot movement is made worse by the prospect that they will have to operate several of them over a short period of time (Edwards, 1984). Furthermore, it is generally understood that the performance effects of subjects using controls which do not comply with compatibility criteria include longer training time, slower speed and increased errors (Murrell, 1965; Oborne, 1987)

The major implication of poor compatibility in robot teach controls can occur during stressful situations. It has been shown that, although incompatible control-direction relationships can be learned, when operators are placed under conditions of stress or distraction they may revert to population stereotype expectations of control-direction compatibility (for examples see Murrell, 1965). This may lead to control errors which, in turn, may worsen the stress situation.

3.5.4 Conclusions

Variations in teach pendant design necessitate quite different control actions to achieve the same movement of a robot. This has been demonstrated in the comparison between the two main types of teach pendant most commonly used for experimental evaluation (Unimate and ASEA). Moreover, such variation can adversely affect control performance reliability especially when an operator frequently uses more than one design (Edwards, 1984; Helander and Karwan, 1988).

CHAPTER 4 - THE MOTION CONTROL TASK

- 4.0 Introduction
- 4.1 Task analysis
- 4.2 The robot motion control task
- 4.3 Human information processing
  - 4.3.1 Human information processing in robot motion control
- 4.4 Factors affecting control reliability
  - 4.4.1 Knowledge and experience
  - 4.4.2 Robot status
    - 4.4.2.1 Human-robot orientation
    - 4.4.2.2 Robot arm-configuration
  - 4.4.3 Control-motion compatibility
  - 4.4.4 Teach pendant design
- 4.5 Framework of robot motion control

CHAPTER 4 - THE MOTION CONTROL TASK

4.0 Introduction

This chapter examines the process by which the operator achieves robot motion; to do this it establishes a framework to represent the task in terms of requirements made on human knowledge and information processing capabilities. In addition to calls for standardisation in teach pendant design, it has been suggested that the control task increases in complexity when changes in human-robot orientation occur (HS/G 43, 1989), although there has been little direct research into the problem. The effects of this and other factors are examined and included in the framework. From this framework some hypotheses concerning task difficulties in robot motion control are subsequently derived.

In this chapter the reader is introduced to a number of terms or concepts which have been developed, adapted or appropriated by the author. These are explained in the text, but as an initial aid the definitions used are;

Human-robot orientation - the position of the operator relative to the robot (e.g. front, back, left or right). This determines the operator's view of the robot.

Robot arm-configuration - the configuration of the individual robot joints. These may be in either 'RIGHTY' or 'LEFTY' arrangements, as described in section 3.3.

Robot status - the conditions of human-robot orientation and robot arm-configuration at any one time are combined to make up the current robot status.

Control-motion compatibility - this is the degree to which the actual direction of motion of the robot arm matches the expected direction, given the direction of the control movement that produced it, as described in section 3.5.3.

Robot movement - this can have two definitions; movement of individual joints or a movement in space from one position to another. In this thesis both definitions apply but under different circumstances;

i) in the joint programming mode, robot movement refers to an individual joint moved in either direction about its linkage, as described in section 3.2.1.

ii) in the world programming mode, robot movement refers to the movement of the Tool Centre Point (TCP) in either direction along the X, Y or Z axes, as described in section 3.2.2. In this situation several joints may be moved simultaneously to produce the TCP movement.

4.1 Task analysis

In the early part of this research work, a task analysis approach was taken in an attempt to identify the elements of the programming task that may expose the programmer to danger (Gray and Wilson, 1988; 1989). Several industrial sites were visited; TI Cox, Nottingham; GEC Plessey, Nottingham; and Ford Transit Plant, Southampton, and the author carried out different levels of observation at each depending upon the time and resources (i.e. programmers) available.

The local plants are relatively small users of industrial robots; TI Cox use a few Unimate PUMA robots and the German-made Cloos (both articulated type robots) for spot welding of small components. GEC Plessey use two Unimate PUMA robots for pick and place tasks. Due to inconsistencies in batch components used at TI Cox, the positioning of each weld was frequently checked and adjusted where necessary. The operator who fed and removed each component was responsible for checking weld accuracy and also fine-tuning the robot program to accommodate for batch differences. Thus, one operator was completely responsible for one robot only. The author was permitted access to one of the PUMA work cells and observed the operator's actions over several hours of work. At GEC Plessey the PUMA robots performed their operation unattended in an enclosed perspex cage. Since the operation was repeated exactly there was very little need to monitor or adjust the program. Thus the author did not get the chance to observe the programming operation nor to interview programmers.

The Ford Transit Plant is a much larger user of industrial robots with five different types and over a hundred in all. This visit provided the author with most of the information for the task analysis work. These robots and their associated teach controls are shown in Appendix I. A great deal of time was spent observing in detail the programming procedure for each robot type (about two days per robot). This was carried out not on the production line but in the maintenance and research laboratory where surplus robots were kept. Several programmers (four in all) were made available to the author and they demonstrated the types of operations normally programmed and the procedure this required for each robot type. In addition, the author was permitted access to the production line and carried out semi-structured interviews with the programmers on-site. The majority of the robots are used on one of three completely automated lines dedicated to a specific part of the production process, and each line has several types of robots, but a predominance of one type. The operators were responsible for all forms of human-robot interaction; programming, maintenance and throughput of material in their line. They worked on only one line but performed all necessary activities within that line. There were on average five operators per line at all times; thus the author carried out interviews with fifteen operators.

An interesting observation was that on each line the operators stated a preference for the teach control of the predominant robot (i.e. the one that they used most frequently) and this was a different robot for each line, which supports the observations of 'negative transfer' when different teach pendants are used made by Edwards (1984) and Helander and Karwan (1988). Good and bad features were identified for all of the teach pendants and the author was able to identify criteria of teach pendant design that were important to these operators. These are shown in Table 4.1, but it should be noted that they are not listed in any order of importance. Understandably, many of these criteria concern program control rather than motion control (defined in section 2.2) as this activity takes up most of the operators' time. However, as has already been mentioned (in sections 1.1 and 2.2), this research focusses on motion control only and so the issues surrounding program control will not be examined further. The criteria concerning motion control were that the motion keys should relate to actual robot movement and should be positioned so that the operator can position his fingers on the keys without having to keep looking at them. For this reason the labelling of motion keys was not considered too important.

On the basis of these visits, forms of hierarchical and tabular task descriptions, preparatory to task analyses, were constructed (Drury, 1983; Singleton, 1974; Stammers et al, 1990). Examples of these are shown in Figure 4.1 and Table 4.2. These descriptions are of the author's own adapted format, and represent the overall task in general terms, including robot

Table 4.1 Design features of teach pendants defined by robot programmers

Criteria	Comments/preferences
Weight	Light weight
Size	Easily held in hand
Display	Must be readable in the environment. Should help you to know what's happened and where you are in the program. Should provide status information and knowledge of external input signals.
Step back/ forward facility	Saves having to type in program step number
Amount of control via pendant	Just moving robot or creating whole program. Main console should never override teach pendant when in use.
Program input	Easier to insert functions with dedicated keys, but this would complicate pendant design (many keys).
Key size	Smaller keys have reduced clarity of labelling. Perhaps use colour or standard abbreviations.
Motion keys	Must relate to actual robot movement. Most at FORD are relative to axis reference positions (cartesian type). Labelling not so critical because programmer doesn't look at the keys, he looks at the robot all the time. He may need to position his fingers on the keys first.
Size and weight of communications lead	If very heavy, it is awkward to move around freely with the teach pendant.
Dead Man's Handle (DMH)	In all cases, releasing the control motion keys would stop movement of that axis. But for safety, an additional DMH with constant pressure should be provided to ensure no robot control when released.

Figure 4.1 Hierarchical task description for programming the PUMA 560 (Mk 1) robot

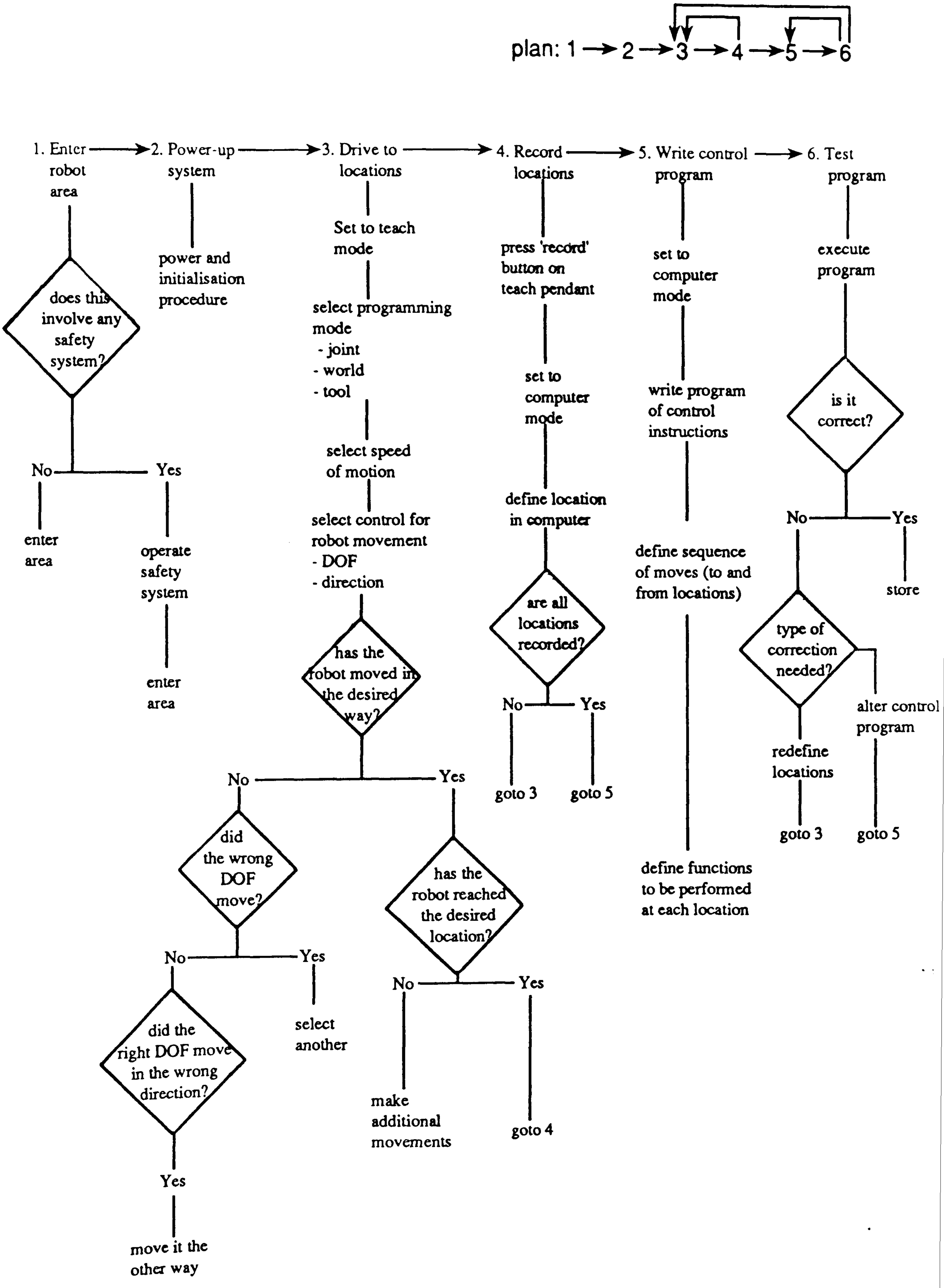


Table 4.2 Tabular task description for programming the PUMA 560 (Mk 1) robot

GOAL	SUB-GOAL	OPERATOR ACTIONS
1. Enter robot area	1.1 Follow appropriate entry procedure	Application specific.
2. Power-up system		Turn key on controller panel one step to the left. Press arm power on button Select computer mode on teach pendant. Type 'CAL' at terminal..
3. Drive to locations	3.1 Select programming mode	Press appropriate button on teach pendant (joint, world or tool).
	3.2 Regulate speed of movement	Move speed selector switch to required speed (fast/medium/slow).
	3.3 Select degree of freedom to be moved	Move appropriate toggle-switch in the required direction (+/-).
4. Record locations	4.1 Computer mode	At computer terminal type "HERE" together with a location name (e.g. 'PLACE').
	or	Within control program type "T" for joint-interpolated motion, or "TS" for straight-line motion, together with a location name.
	4.2 Teach mode	Press the 'REC' button on the teach pendant to record the current location of the robot and each subsequent location required.
5. Write control program	5.1 Access program	To either create or edit a program type "EDIT" together with the program name. Type each instruction on a separate line as prompted.
	5.2 Specify move instructions	Type "MOVE" together with the required location (e.g. MOVE PLACE). Alternative commands are; "MOVET", "MOVES" or "MOVEST".
	5.3 Specify functions to be performed	Use VAL commands such as; "OPENI" to open gripper, "WAIT 1" to wait for external input signal, "GOTO" subroutine when input signal is received, "DELAY" for a specified time, "APPRO" to approach a position at a specified speed, "DELAY" to depart from position by a specified amount.
6. Test program	6.1 Remove control from teach pendant	Press 'COMP' button on teach pendant.
	6.2 Initiate relevant safety procedures	e.g. shut interlock gates.
	6.3 Run program	Type "EX" together with program name.

start-up, program control and motion control. As previously noted, this research is focussed on motion control only. Other aspects will not be examined further, other than to note two observations: the procedure for program control varies considerably between robot systems, and, although the design of controls vary, motion controls share the same functions between different robot systems.

With reference to goal 3 (drive to locations), in Table 4.1, it can be seen that there are four factors which determine how the robot will move; the programming mode (joint, world or tool), the particular degree of freedom controlled (joint or axis), the direction and the speed of movement (see Figure 4.2). All four factors must be set in order for the robot arm to move.

Other attempts at defining or analysing the robot teach control process are presented by Parsons (1986b) and Rahimi and Azevedo (1990). Following a survey of ten different robot systems (previously discussed in section 2.2.1), Parsons (1986b) produced a task taxonomy of industrial robot programming. The part of this taxonomy relating to motion control is shown in Table 4.3 which provides a listing of the task elements similar to those identified by the author in Figure 4.2. Rahimi and Azevedo (1990) portray the sequence of activities performed during a set programming task using a PUMA 560 robot (see Figure 4.3). Unfortunately, this could have been derived by simply recording the instructions provided in the PUMA programming manual. Having outlined the basic task, Rahimi and Azevedo then measured performance errors of trained programmers and it was found that direction errors when moving the robot arm were predominant. Furthermore, they found that more movement direction errors occurred when the robot was programmed in joint mode than in world mode. They concluded that the cause of these errors lay in the inefficient design of the teach pendant, and claim that their results emphasise the need for standardisation in teach pendant design. Unfortunately, they offer no detailed information on the actual process of robot motion control, nor do they indicate how many directional errors were made and in what circumstances they tended to arise.

Figure 4.2 Factors required for robot movement

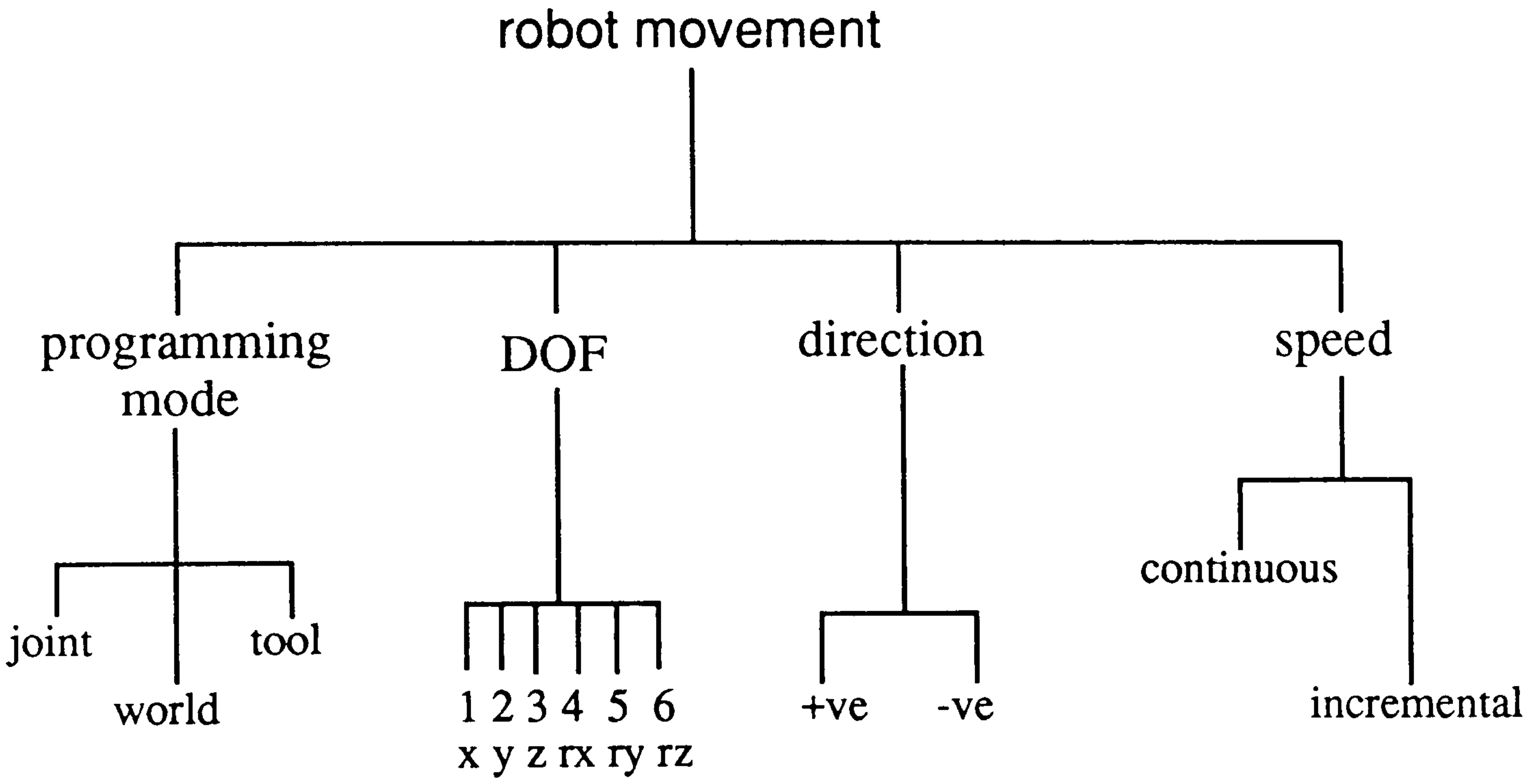
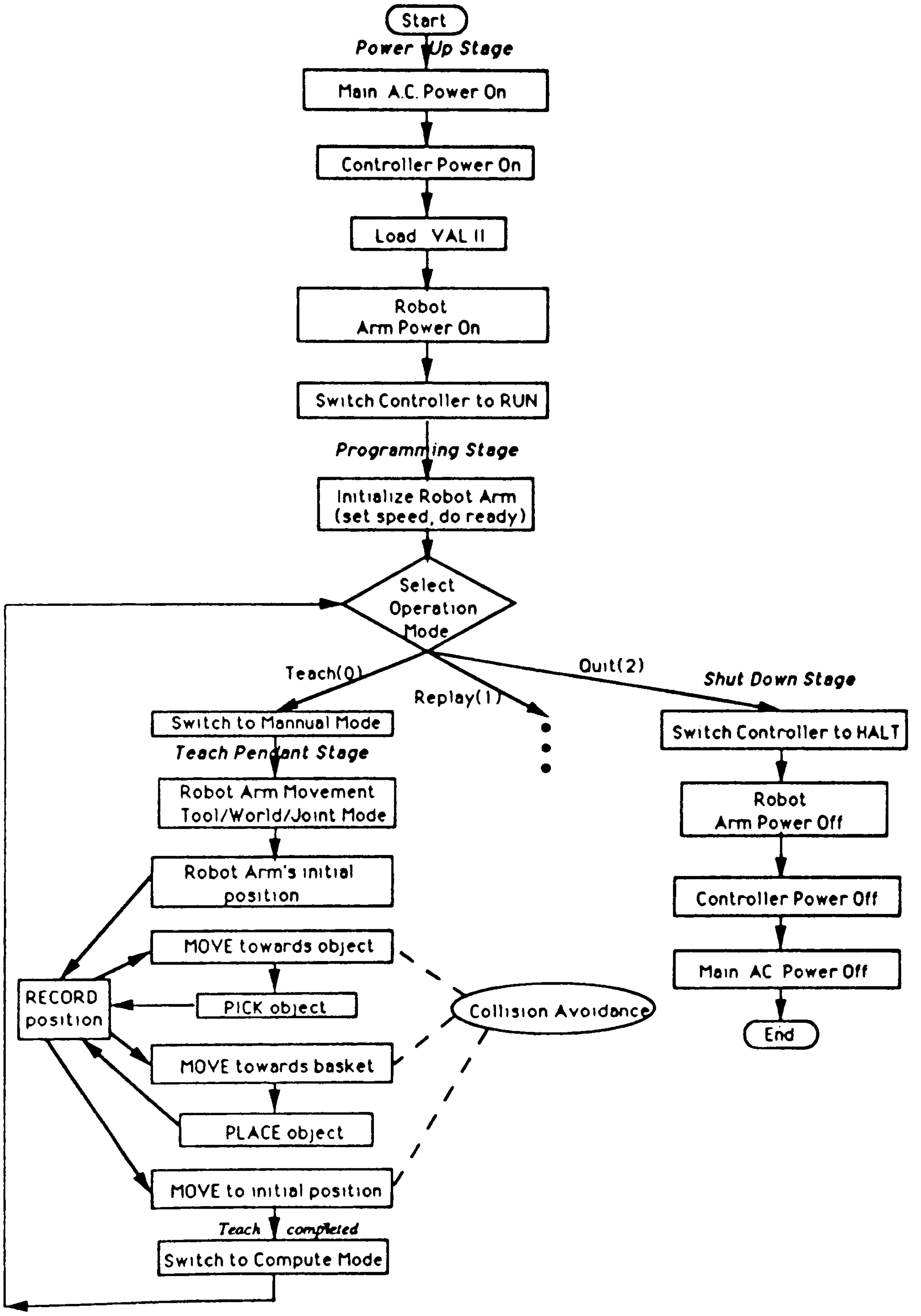


Table 4.3 Part of the taxonomy of the robot control task produced by Parsons (1986b)

1. Preliminaries:
    a. Calibrating robot axes.
    b. Checking software stops.
    c. Selecting initial reference point (origin).
2. Enabling the teach pendant.
3. Selecting the type of robot movement by the teach pendant:
    a. Along rectangular axes by arm joints.
    b. Along angular axes by wrist joints.
    c. Along individual joint axes.
    d. Free motion (no pendant control).
4. Selecting the origin of the coordinate frame for pendant movement:
    a. Robot base (world frame).
    b. Wrist flange (tool frame).
    c. Other origin (user frame).
5. Selecting the speed of teach pendant movements.
6. Moving the robot with the pendant to each planned destination location.
    a. In position.
    b. In orientation.
7. Aligning the tool with the workpiece:
    a. Close visual observation.
    b. Precise positioning and orienting.
8. Recording the position and orientation for each location:
    a. Acquiring the program identifier of the location.
    b. Activating the "record" or "write" button.
    c. Alternatively, typing a command at the terminal.
9. Modifying locations and coordinates:
    a. Deleting a location name and its coordinates.

Figure 4.3 Task analysis of robot programming produced by Rahimi and Azevedo (1990)



All these examples of task analyses or descriptions, including the author's own, in fact are little more than task descriptions. These, on their own, are not sufficient to provide any assessment of difficulties in robot motion control. Although task descriptions were produced for five robot systems in total, the approach seemed not to provide useful insight into the main issues of concern. Thus, only example task descriptions have been reproduced here. Moreover, within the experimental assessment of task performance carried out by Rahimi and Azevedo (1990), the task analysis approach used to describe the control process enabled them only to state in what part of the process errors occurred (i.e. control of motion) but not why.

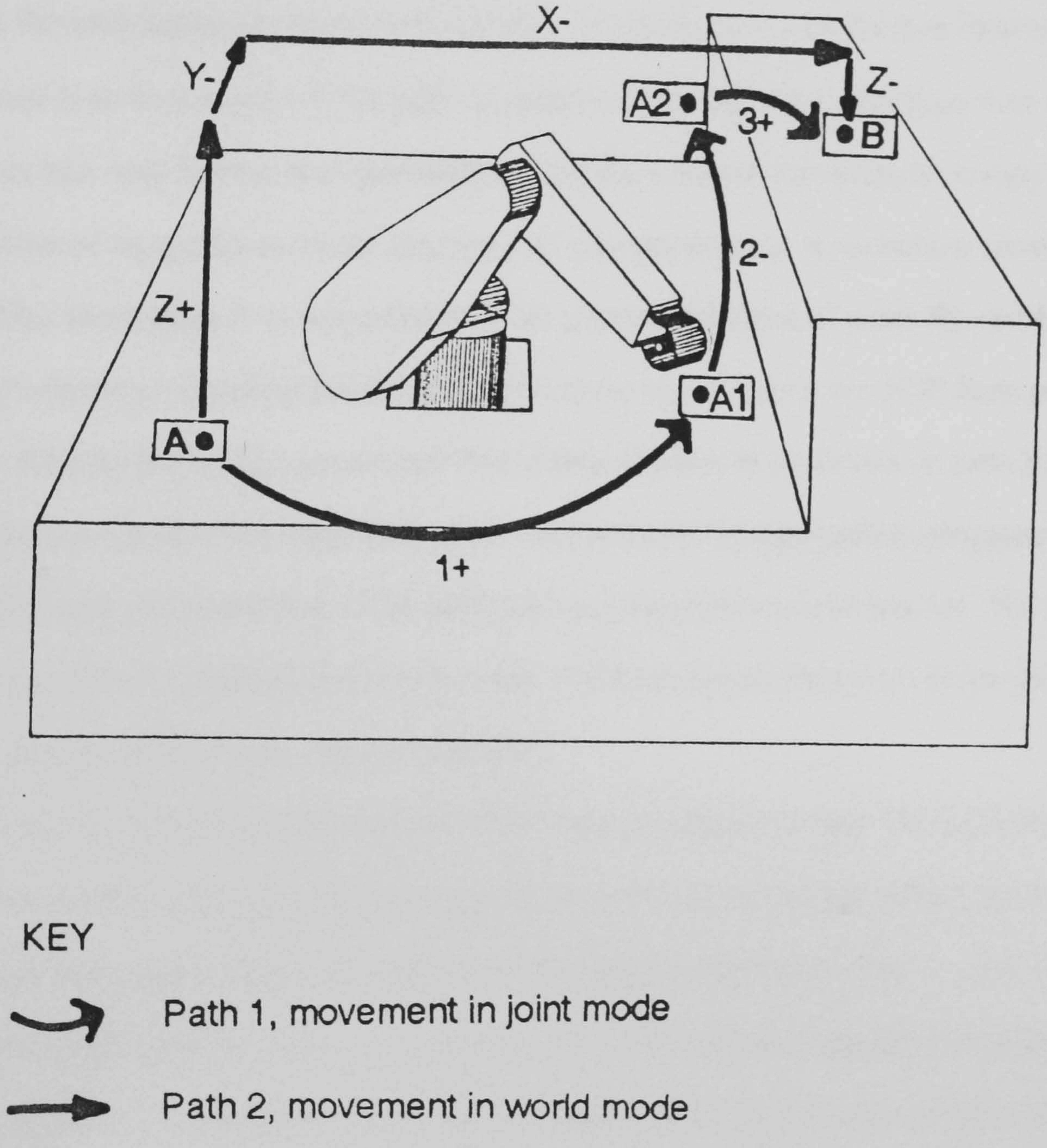
It seems that an alternative method is required to represent human-robot interaction during the motion control task, from which assessment of performance reliability can be made. Therefore, it was decided to abandon more traditional task analysis methods and to consider the task in terms of human-information processing requirements; this might help to identify difficulties within the task that cause errors in motion control. These will be discussed in detail later in the chapter, but first it is helpful to outline a typical example of a motion control task to provide the reader with a visual illustration of the concepts that will be discussed.

4.2 The robot motion control task

In order to move an industrial robot from one location to another, the operator needs to make certain decisions concerning how the robot arm is to be moved in terms of; programming mode, degree of freedom, direction, speed and amount of movement. A simplified example of a motion control task with two alternative paths is illustrated in Figure 4.4.

The robot is required to pick up a block at location A , move it to location B and release it. Two alternative paths are shown that could be used to move the block from A to B. Path 1 uses joint mode movements only and in this example requires three individual moves (1+, 2-, 3+). Path 2 uses world mode movements only and four individual moves are illustrated (Z+, Y-, X-, Z-). Of course, there are many other paths that could be taken, some of which would combine movements in joint, world and tool modes of programming. The restrictions on the path of motion actually taken are the reach envelope of the robot arm, the limit range of the

Figure 4.4 Two possible alternative paths for moving the PUMA robot from point A to point B

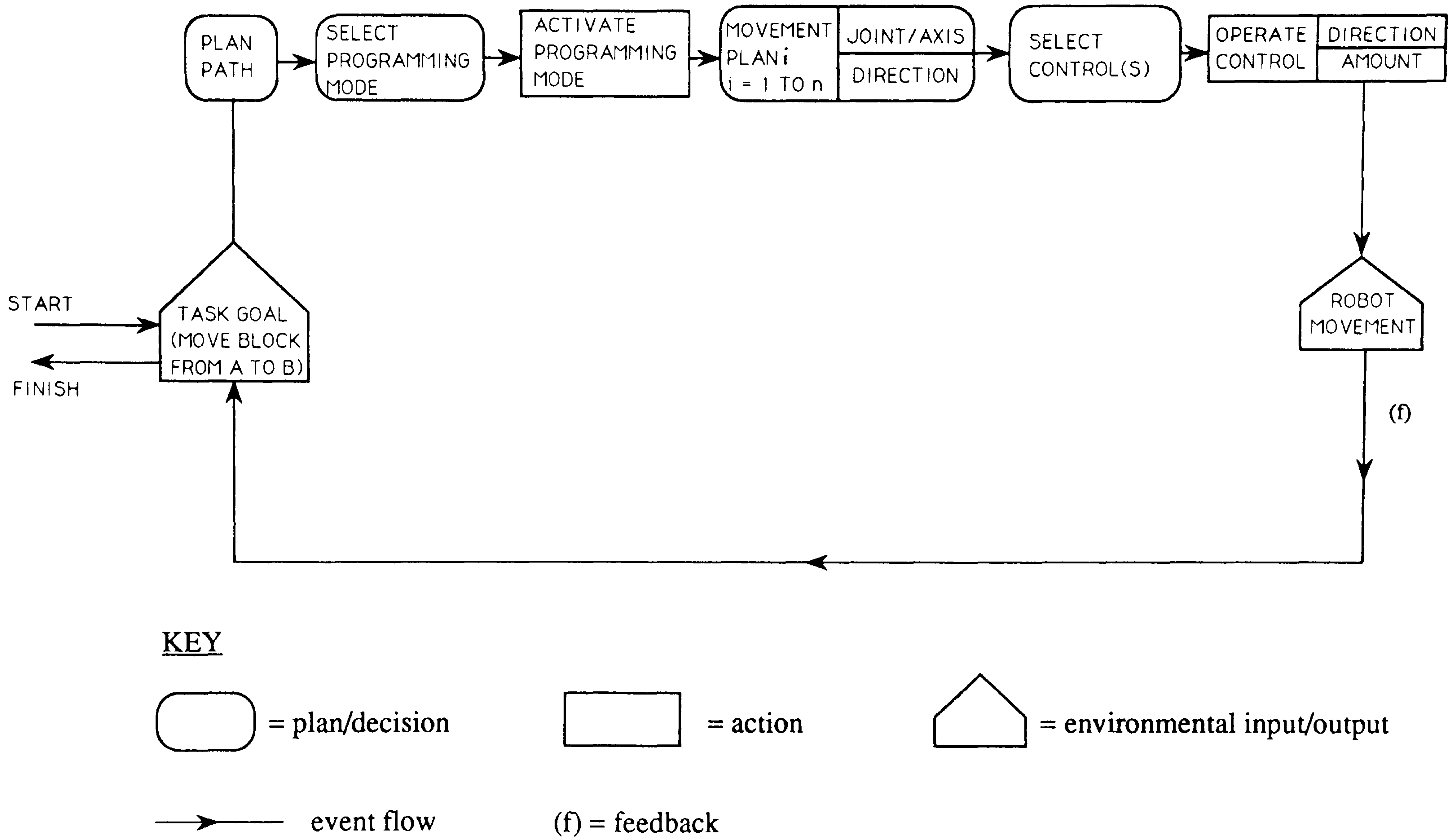


individual joints and any obstacles inside the robots' movement range.

A representation of the motion control task is shown in Figure 4.5. This shows the sequence of decisions and actions that are required to achieve robot movement, and is akin to a form of task description such as those reproduced in section 4.1. However, it should be noted that whilst the sequence of actions is as represented, the author makes no assumptions that the decisions for each action are made sequentially. It can be seen that the first decision made by the operator is to form a plan of the path of motion to get the robot arm from A to B. This may be more or less well formed and specified, within the mind of the operator; it may consist of a vague notion of approximate order and types of movement (e.g. to somehow move the Tool Centre Point from point A to somewhere in the general direction of point B), or of almost an exact and complete representation of what will occur (e.g to move the TCP from point A upwards, then back slightly, across and then down to point B as shown in path 2). Having made this plan, the operator must then select and activate the appropriate programming mode, based upon their understanding of the task goal and the plan formed thus far. For instance, if path 2 is specifically planned, the world mode will be selected; however, if the plan is vague, then any programming mode may be selected.

Next, the operator must plan the first individual movement to take the robot from one position to another (e.g. movement from point A to A1 would require joint 1 to be moved in the positive direction). Again, this plan may be specific (e.g. move joint 1 120° in the positive direction to reach point A1, then move joint 2 75° in the negative direction to reach point A2, etc.), or vague (e.g. move joint 1 until the TCP approaches the direction of point B and then make a new plan). The appropriate control on the teach pendant for the individual movement required is then selected and robot movement is achieved by operating this control a certain amount in a certain direction. The notion of a plan at this stage of the process is different to the path plan previously described because it must be defined before control selection is made or the operator would randomly activate the motion controls. This does not imply that the individual movement plan will necessarily be correct, but that it is a necessary precursor to control activation, whereas the path plan may be formulated during the task. Finally, the

Figure 4.5 Representation of the robot motion control process



operator receives feedback of control actions by observing the resulting robot movement and may need to correct or modify the path plan or individual movement plan(s) if the desired goal has not been achieved. Thus feedback may go back to any one or several of the decision stages. However, these links are undefined and therefore in Figure 4.5 feedback is represented only as completing the control loop.

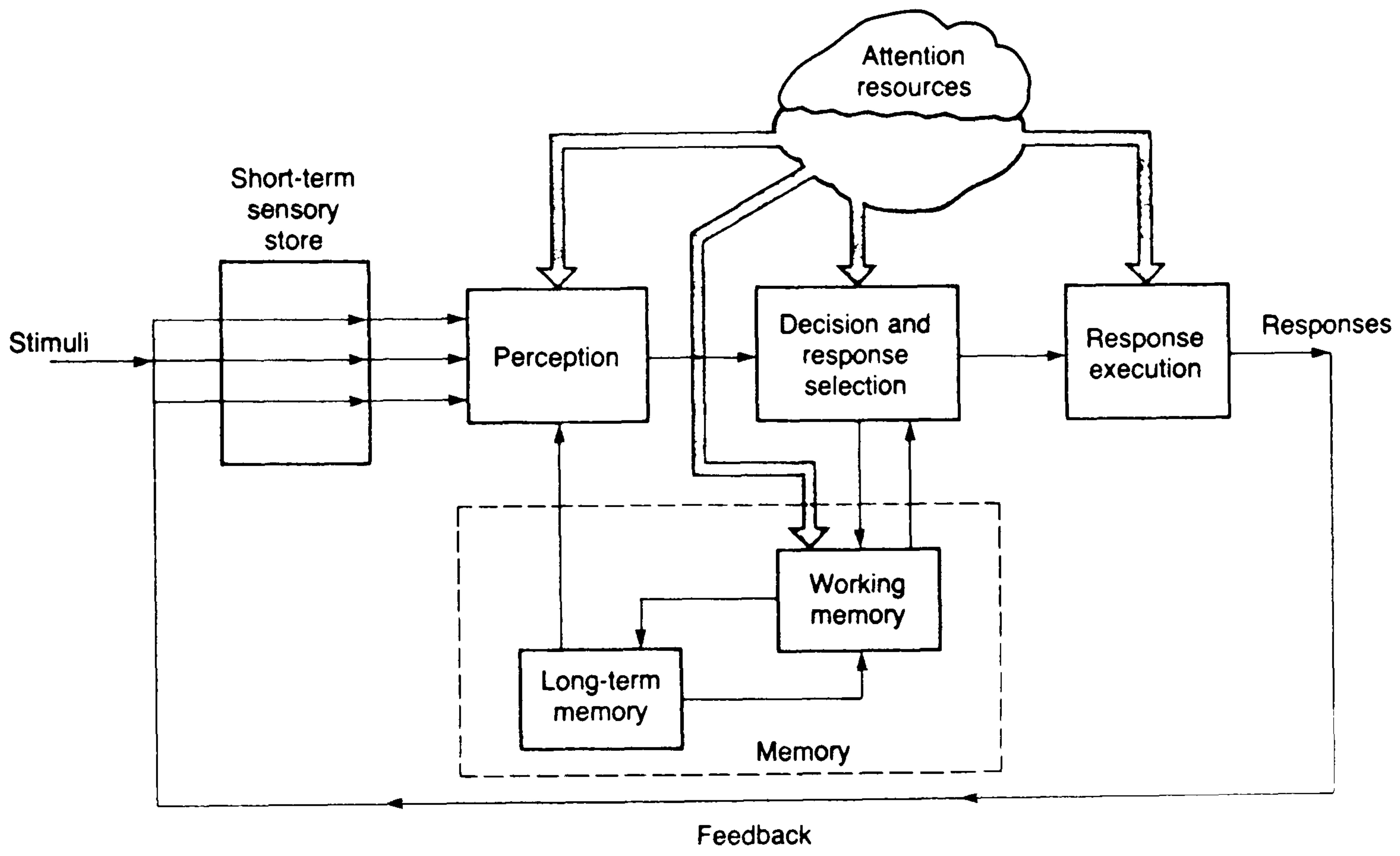
The representation shown in Figure 4.5 is, of course, a great simplification of the motion control task , particularly in the way that it shows the sequence of activities to be linear or serial. Many assumptions have been made concerning the possible ways that an operator may go about this task but the author feels that these are reasonable assumptions which provide a good basis on which assessment of motion control performance can be made.

Representation of the motion control task as a series of decisions and actions in this way leads the author to an assumption of the operator's role as 'information processor' in the control of robot motion. To this end, human information processing theory may be used to enhance our understanding of reliability in robot motion control.

4.3 Human information processing

One model of human information processing, currently widely employed in human factors research, is shown in Figure 4.6 (Wickens, 1984). This model represents the cognitive processes believed to underlie human performance in response to environmental information. The basic features of the model are that the information arrives at the receptors (eyes, ears, etc.) and is held in short-term sensory storage where some initial encoding takes place. The process of information perception involves identification and recognition, making sense of the information on the basis of the situation and the person's knowledge and experience. A decision is then made as to what action, if any, needs to be taken and the appropriate response action is then carried out. The result of this response action provides feedback for the observer. In order to perform in this way, a person requires storage and processing capacity; working memory is said to provide a short-term memory store and to control all stages of information processing, whereas long-term memory is where all of what is termed

Figure 4.6 A model of human information processing



Source: Wickens (1984)

'knowledge' is permanently held, in some form of mental representation. In order to do all this we have finite attentional resources which must be allocated in optimal fashion.

Early theories of human information processing maintained that each processing stage was carried out in sequence and that the flow of information was unidirectional (Sternberg, 1969). This view has been criticised by many authors (e.g. McClelland, 1979), arguing that the stages may operate in overlapped sequence, and may not be one-way or sequential in their execution.

In an attempt to discover more about these cognitive processes, much experimental work has measured human performance in terms of reaction time. This is because it is assumed that each processing stage takes up a certain amount of time which will vary in accordance with task difficulty. The findings suggest that; response time is influenced by uncertainty of choice (Hick, 1952; Hyman, 1953), uncertainty of choice increases if stimuli are indiscriminable (Miller and Pachella, 1973), and response time will increase if there is a high degree of stimulus-response compatibility (Salvendy, 1983). The accuracy of response output has also been measured and it has been found that error rate will increase when there is little or no stimulus-response compatibility, or when uncertainty of choice is increased (Broadbent, 1971).

The assumption could be made, therefore, that in a comparison of performance using two interface systems, the one which produces the fastest peformance may also produce the least errors (Wickens, 1987). However, there is one situation when the relationship between reaction time and error performance is reversed, and this is when emphasis for the subject is placed on either one. This is known as the speed-accuracy trade-off and produces the effect that efforts to increase reaction time will be at the cost of less accurate performance and vice-versa (Pachella, 1974).

The focus of attention for psychologists has been, and still is, to measure and define the basic features of a human information processing model in the search to describe and explain behaviour. It is the practical application of any model that is of most interest to ergonomics, since it can help to determine how information should be conveyed and the best design of controls and displays in applied contexts.

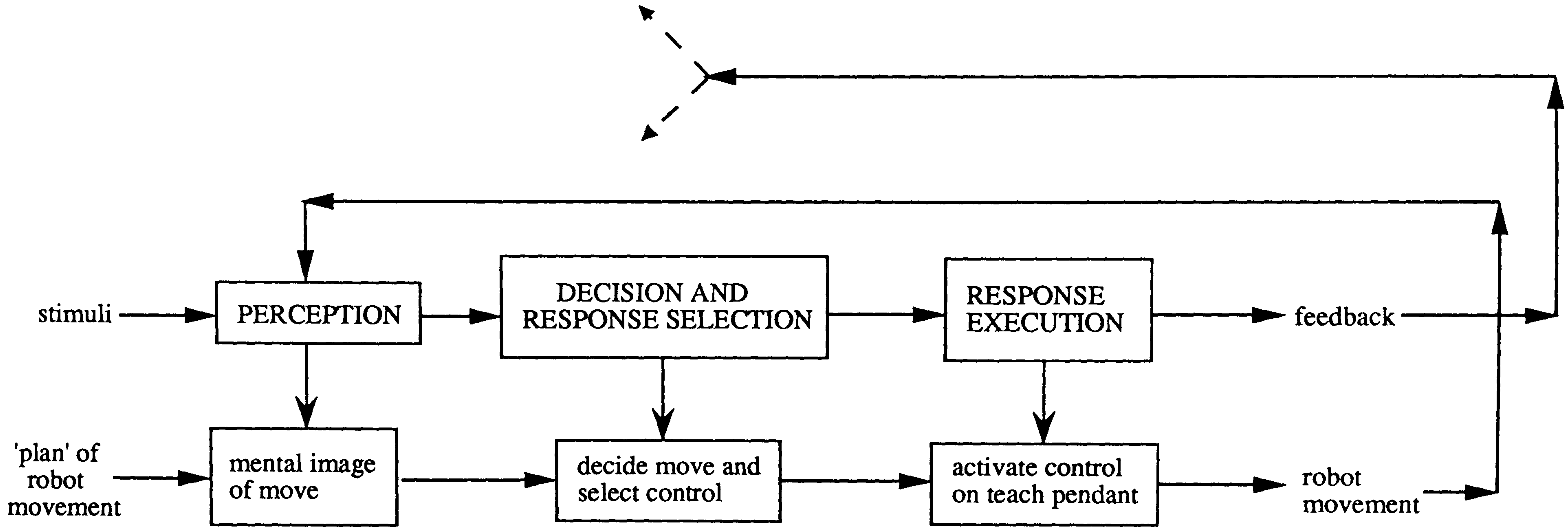
Competitor models, or ideas and theories for models, such as connectionist theories, are not yet developed in a way to be useful to ergonomists. The human-information-processing model, however, appears to be a useful aid to understanding more about the robot motion control process and the potential causes of performance errors.

4.3.1 Human information processing in robot motion control

It is not anticipated that robot motion control (as against program control) will tax attention resources. Likewise, limitations of memory as information storage are not of prime interest at this time. What is of main concern are the potential problems involved in information perception, decision making and response execution that may lead to errors in robot motion control. Thus, application of the human-information-processing model to the robot motion control process will concentrate on these elements only.

Figure 4.7 represents the robot motion control process in terms of these human-information-processing requirements. It can be seen that the information for the task is the plan of robot movement defined by the task goal, and may be at two levels as previously described in section 4.2; a general plan of the path that must be taken (e.g. path 1 or 2 as shown in Figure 4.4), and a more specific plan of the individual movements to get from A to B (e.g. A to A1, A1 to A2, etc). At this stage the information does not come from an external source to be visually perceived by the operator (i.e. the robot has not actually moved), but is derived from the operator's 'internal representation', in whatever form it may take, of robot movement. The decision process involves recognition of the actual robot movement required (e.g. to move from point A to A1, joint 1 must be moved 120° in the positive direction). Thus, the operator must decide on the programming mode required, the degree of freedom to be moved, the direction it should be moved in, and the amount of movement needed. Then

Figure 4.7 Application of human information processing to robot motion control



decisions must be made as to which control(s) on the teach pendant will achieve this movement (e.g. to move joint 1 from point A to A1 using the toggle-switch pendant, the 'joint mode' button must be selected and the top toggle-switch moved to the right as shown previously in Figure 3.11). Finally, the response execution is achieved by activating the chosen control(s) on the teach pendant. The resulting robot movement provides visual feedback to the operator, for comparison with the 'internal representation plan' of that movement.

4.4 Factors affecting control reliability

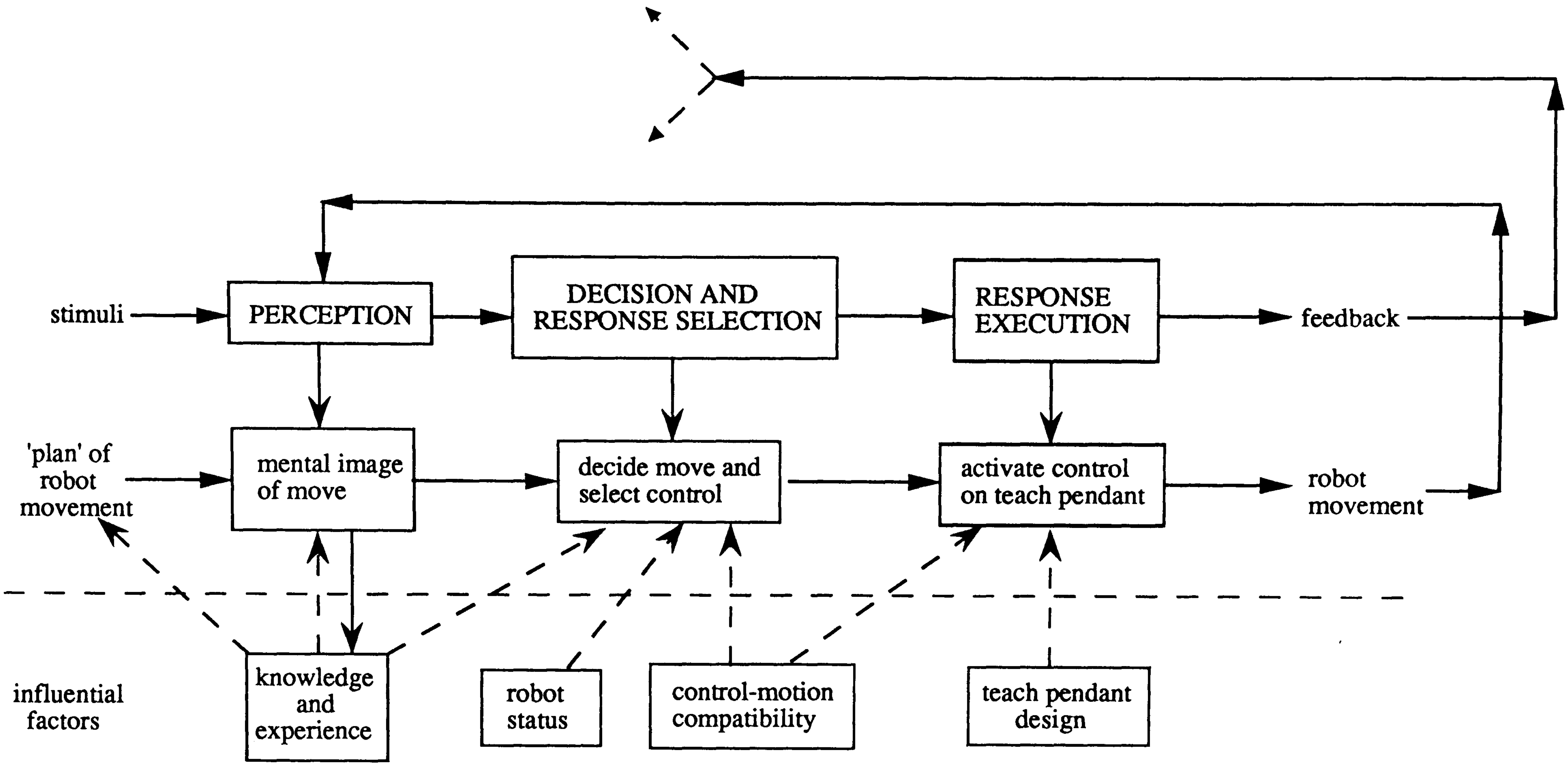
The representation of the robot motion control process shown in different formats in Figures 4.5 and 4.7, are still somewhat simplistic and offer no more details of the likely causes of performance errors than do the task analysis methods discussed in section 4.1. Thus, further information needs to be added to the representation.

Figure 4.8. includes four factors which may potentially influence reliable performance at each information processing stage. These are the knowledge and experience of the operator, robot status, control-motion compatibility, and actual teach pendant design. These factors represent human characteristics as well as situational conditions and control design factors. They are not definitive and their relationship with the information processing stages may not be as simple as is shown. However, it is a reasonable assumption that these relationships exist as will be discussed in the following sections.

4.4.1 Knowledge and experience

The operator's knowledge of the robot system and its movement capabilities, and their experience at the programming task, are factors which can determine their approach to achieving the task goal. For example, at a very simple level, if the operator is unaware of robot movement in joint mode, they will not be able to plan the path of movement from A to B shown as path 1 in Figure 4.4. Similarly, if they are unfamiliar with the range of robot movement in this mode, they may make a path plan that would involve joint movements beyond their physical or programmable limit range. In Figure 4.8, therefore, knowledge and

Figure 4.8 Potential factors influencing performance at each cognitive processing stage



experience have been shown to influence both the planning of the robot movement path and the internal representation that the operator will have of this path and its constituent moves. From the diagram, it can also be seen that visual feedback of actual robot movement provides information perceived by the operator that will add to their knowledge and experience. This may confirm that their internal representation of a particular movement is correct or inform them that it is incorrect, in which case an alternative internal representation of that movement may be produced. For example, if the operator incorrectly decides that the movement from point A to A1 is produced by moving joint 1 in the negative direction, and activates the '1-' control, they will see the robot arm move away from point A1 not towards it and may amend the internal representation of negative movement of joint 1. The operators' knowledge of robot movement can also influence their ability to define the individual moves required (e.g. the decision that the move A to A1 is produced by moving joint 1 in the positive direction).

4.4.2 Robot status

It has already been mentioned that changes in human-robot orientation are believed to make the control task more complex (see discussion of Creed's experiment, section 2.2.3). This is because the effect of changing human-robot orientation, by movement of the person around the robot, alters the view of individual robot movements for the operator, and thus it changes their perspective. Due to the additional movement flexibility of the jointed-spherical type robot, this effect can also be produced by changes in robot arm-configuration. The effect of both these changes together can be extremely confusing. In this research the conditions of human-robot orientation and robot arm-configuration have been grouped as "robot status". The effects of this are described below.

4.4.2.1 Human-robot orientation

Human-robot orientation refers to the viewing position of an observer relative to the robot (e.g front, back, left or right). The appearance of some individual robot moves in both joint and world programming modes when the observer is positioned at the front of the robot have already been illustrated (section 3.5, Figures 3.11 and 3.12). However, in reality, the observer may need to move around the robot while controlling it in order to get the best view of the workpiece. Some examples of the effect of changes in human-robot orientation on the appearance of individual robot movements in these modes are illustrated below.

Joint mode

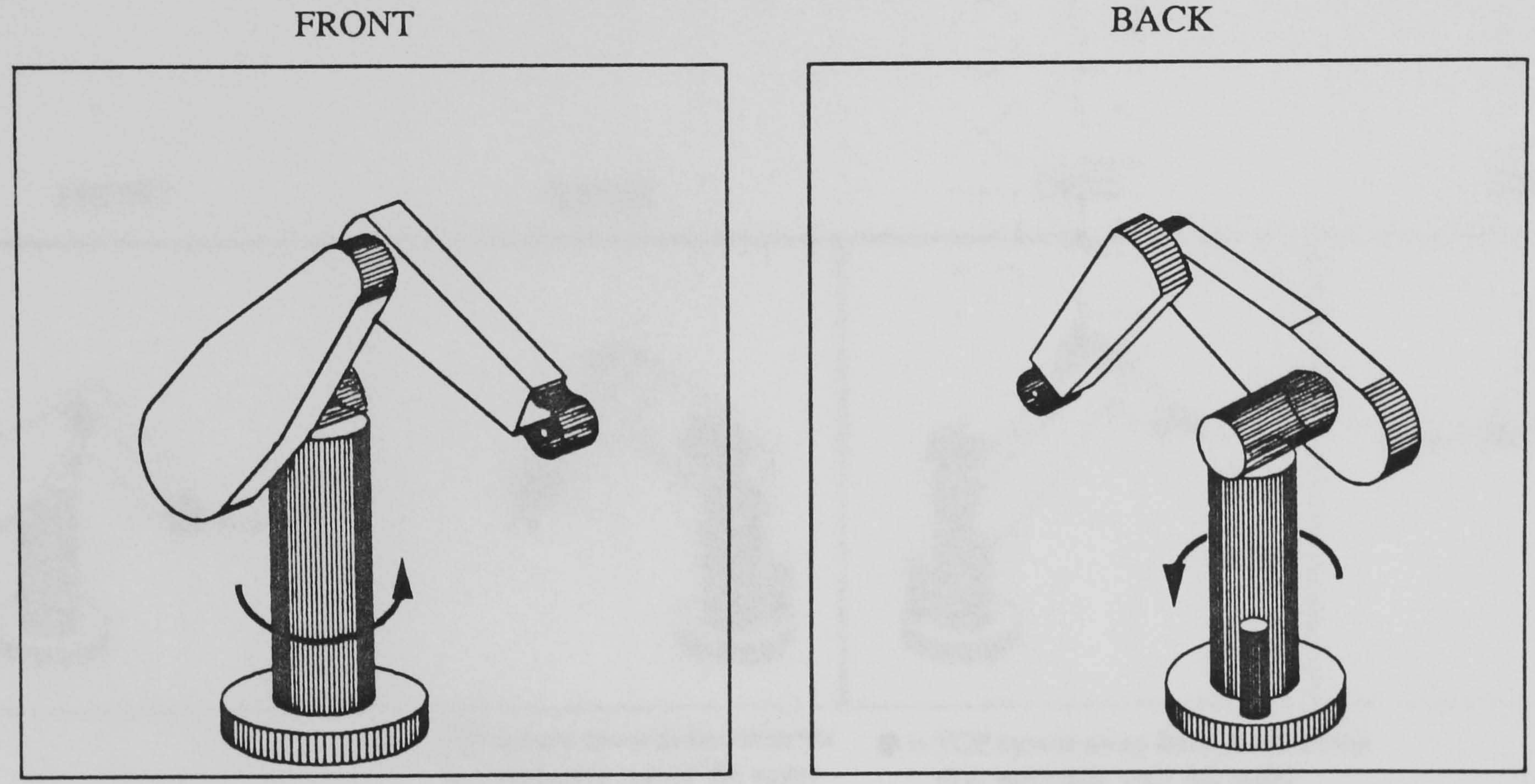
In Figure 4.9, a movement of joint 1 in the positive direction is illustrated as it would be viewed by an observer positioned at the front or the back of the robot. It can be seen that such a change in the observer's orientation to the robot may alter the 'appearance' of the movement from the perspective of the observer. In this case, a movement of joint 1 in the positive direction may appear to move the joint to the right when viewed from the front, but to the left when viewed from behind.

World mode

Figure 4.10 shows a movement along the X axis in the negative direction as it would appear when viewed from the front, right, left and back orientations. It can be seen that the Tool Centre Point appears to move to the right when viewed from the front, but to the left when viewed from the back. At the side orientations the appearance of the move is towards or away from the observer at the right and left orientations respectively.

It is possible that the observer may actually 'perceive' a given robot movement as being different when it is viewed from different orientations. For example, in joint mode, when joint 1 is moved in the positive direction and is viewed from behind, the robot appears to move to the left instead of to the right. The observer may in fact perceive this as a movement of joint 1 in the negative direction and, on this premise, may select an incorrect control on the teach pendant.

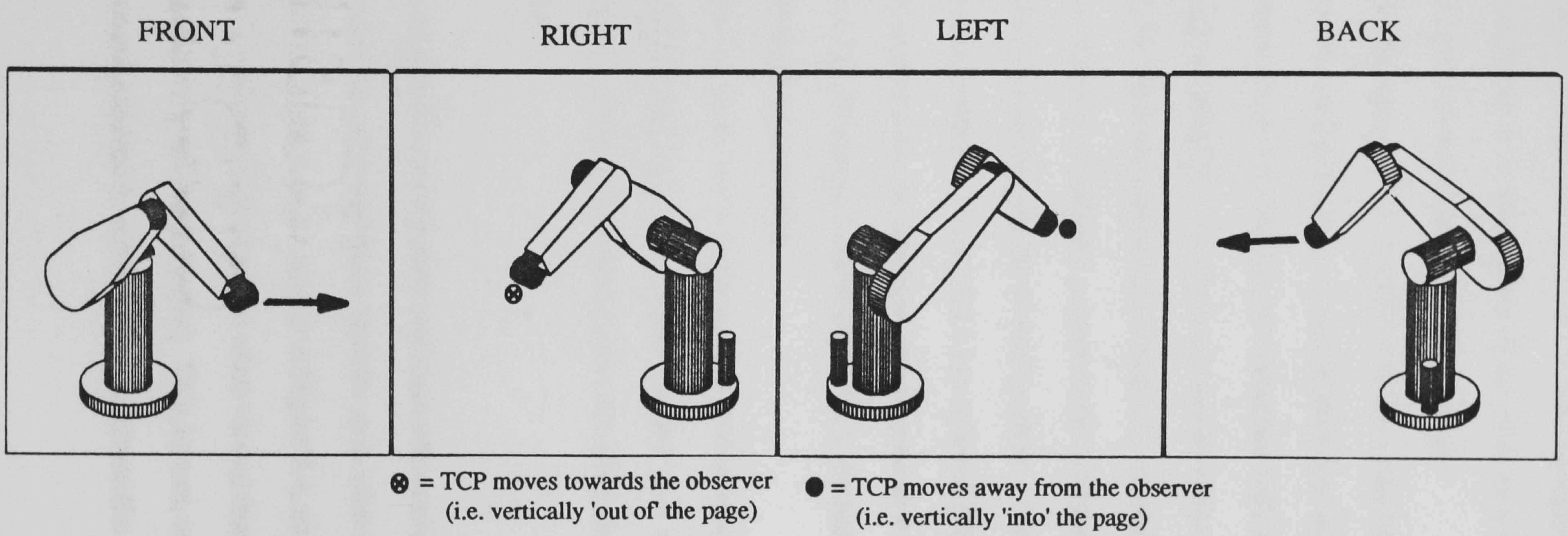
Figure 4.9 Appearance of a joint 1 movement in the positive direction when viewed from the front and back human-robot orientations



FRONT

BACK

Figure 4.10 Appearance of a movement of the tool centre point (TCP) along the X axis in the negative direction, as viewed from different human-robot orientations



4.4.2.2 Robot arm-configuration

The ability of the articulated robot to adopt a 'RIGHTY' or ''LEFTY' arm-configuration has already been described (section 3.3). In Figure 4.11 an example of the effect of a change in arm-configuration on the appearance of robot joint movement is demonstrated.

It is assumed that the RIGHTY arm-configuration is the 'normal ' position of the robot (all previous examples have shown the robot in this configuration). It can be seen that, with this arm-configuration (Figure 4.11a), a movement of joint 2 in the positive direction will move the arm upwards. If the robot then performs an 'arm-flip' movement and hence moves into a LEFTY arm-configuration (Figure 4.11b), the same movement would appear to an observer to move the joint downwards. Of course, the direction of joint movement is still 'positive' but the joint is moving downwards because it has rotated beyond the vertical position. The figure also shows the LEFTY arm-configuration after a rotation about joint 1 has occurred (Figure 4.11c). In this case, the Tool Centre Point is at exactly the same position in space as it was in the RIGHTY arm-configuration (Figure 4.11a). However, a move of joint 2 in the positive direction will cause the arm to move downwards instead of up.

Using the same argument as before, if an observer were to approach the robot which is already in the LEFTY arm-configuration (Figure 4.11b,c), it is possible that they may expect a downward movement of the arm to actually be a movement in the negative direction and, consequently, make a control selection error.

The main point to be made here about human-robot orientation and robot arm-configuration is that their perception of robot status may influence the operator's decision as to what robot movement is required (e.g. the movement from point A to A1 shown in Figure 4.4, may be perceived as requiring a movement of joint 1 in the positive direction when viewed from the front, but in a negative direction when viewed from behind the robot). This, in turn, may lead to incorrect selection of the appropriate control required to achieve that movement (i.e. '1-' instead of '1+').

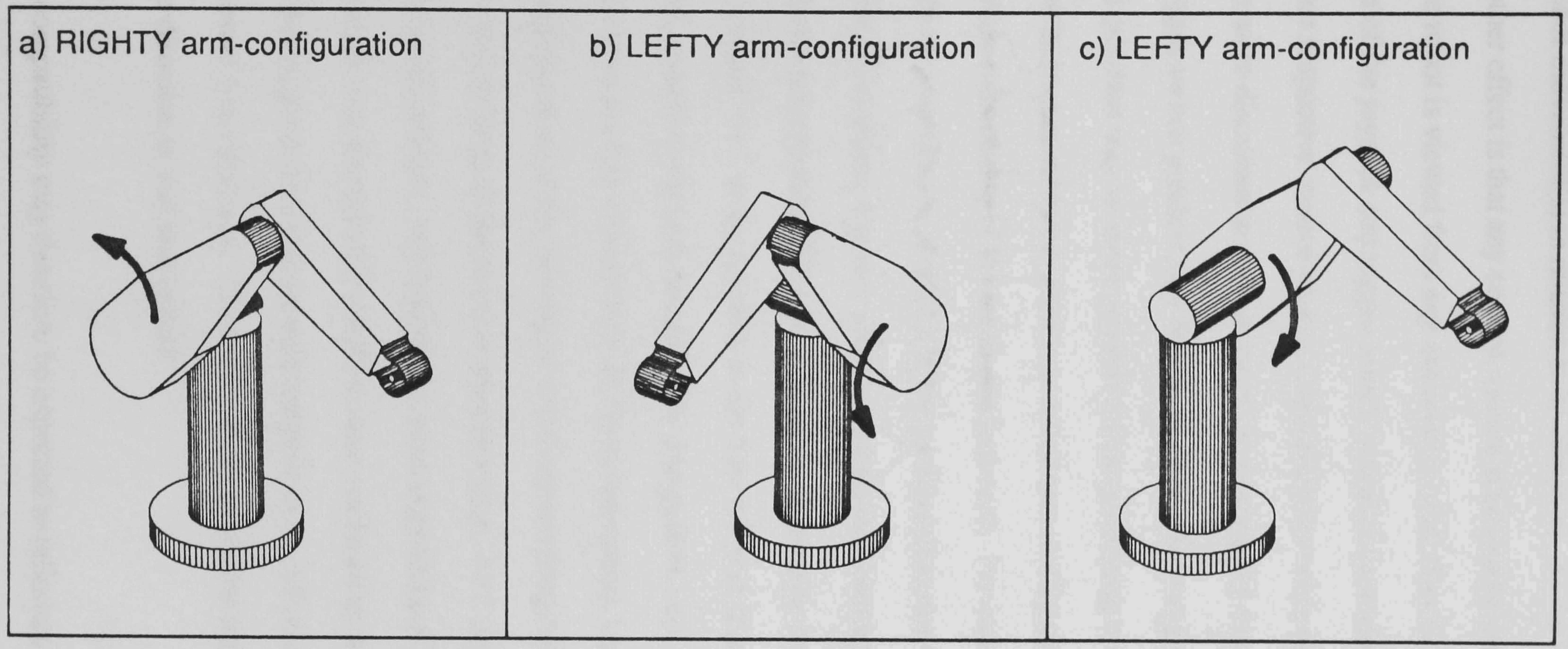


Figure 4.11 Appearance of a joint 2 movement in the positive direction when viewed in different robot arm-configuration positions

a) RIGHTY arm-configuration

b) LEFTY arm-configuration

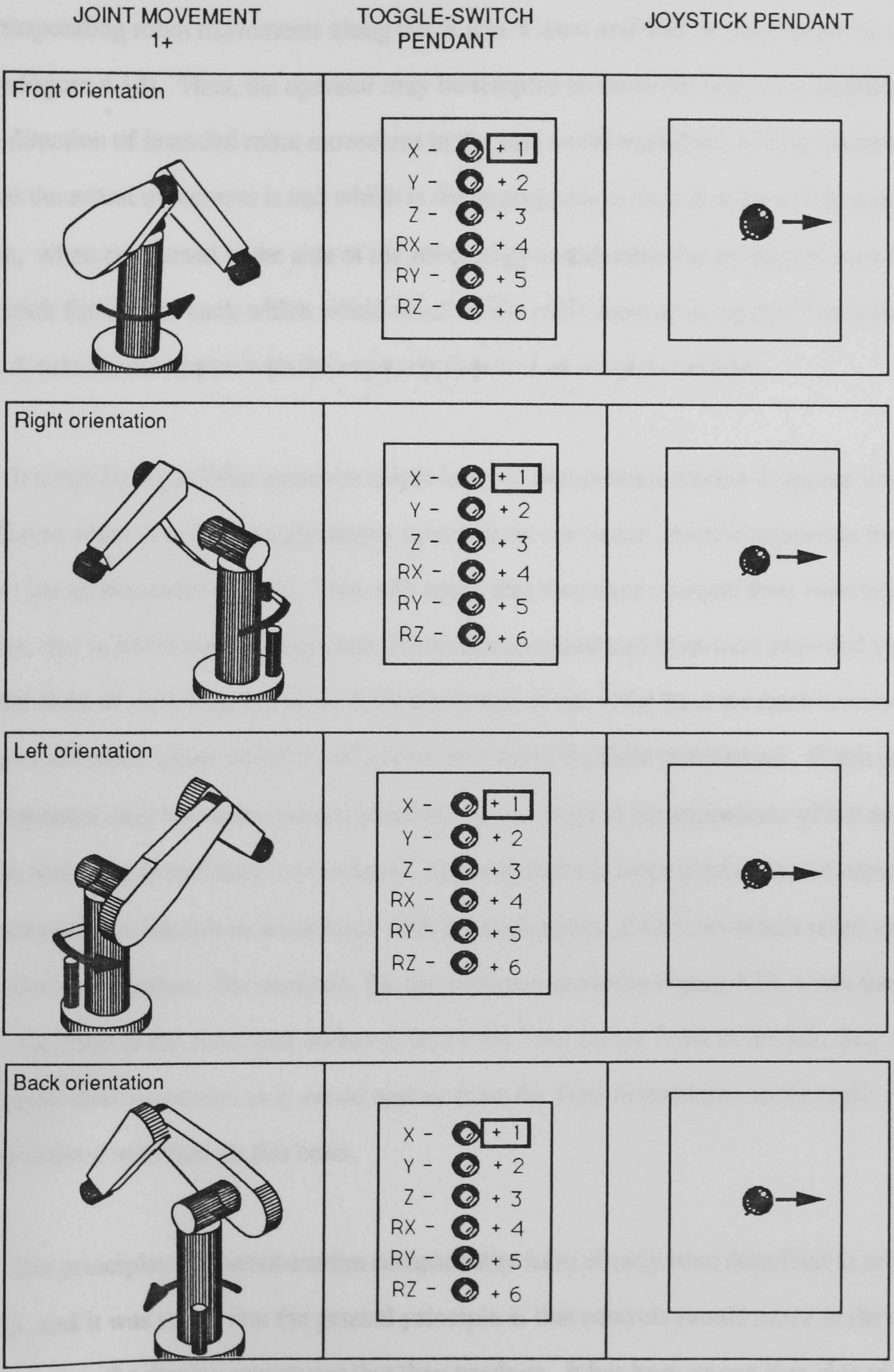
c) LEFTY arm-configuration

4.4.3 Control-motion compatibility

The above examples have demonstrated that the effect of changes in robot status will alter the appearance of robot movement(s) in relation to an observer. As the teach pendant is carried by the operator, another effect is that any control-motion relationship may no longer be compatible when the robot is viewed from any orientation other than the front. The control-motion relationships of the joystick and toggle-switch pendants have already been described in section 3.5.2 and their respective control-motion compatibilities when operating the robot from the front orientation were discussed in section 3.5.3. It was argued that, on the basis of compatibility, the toggle-switch pendant may be more suitable for programming in joint mode whereas the joystick pendant may be more suitable for programming in world mode. Changes in robot status, either in human-robot orientation or robot arm-configuration, will inevitably alter the control-motion relationship of the teach pendant used. For example, Figure 4.12 shows the appearance of a movement of joint 1 in the positive direction when viewed from different human-robot orientations, together with the appropriate control for achieving this movement using either teach pendant. This movement is achieved by moving the top toggle-switch to the right (marked '1+') or the joystick to the right (as was described in section 3.5.2). These control actions could both be said to be compatible with the 'rightward' appearance of the movement when viewed from the front orientation, but are not compatible with the alternative appearances of the movement when viewed from other orientations. It follows that, as the 'actual' move of the robot is the same (e.g. '1+'), then the control action required, using either teach pendant, will also be the same regardless of human-robot orientation. It is possible that the operator could become confused by the change in orientation and expect to move the toggle-switch and joystick controls to the left to achieve this move when the robot is viewed from the back. The result of this would be that the robot would move in the opposite direction to that anticipated.

Control-motion compatibility may therefore be expected to influence the way in which the operator uses the teach pendant. It has been shown that different teach pendant designs will vary in the amount of control-motion compatibility they provide and in the conditions which

Figure 4.12 Changes in control-motion relationships using the toggle-switch and joystick teach pendants when robot movement is viewed from different human-robot orientations

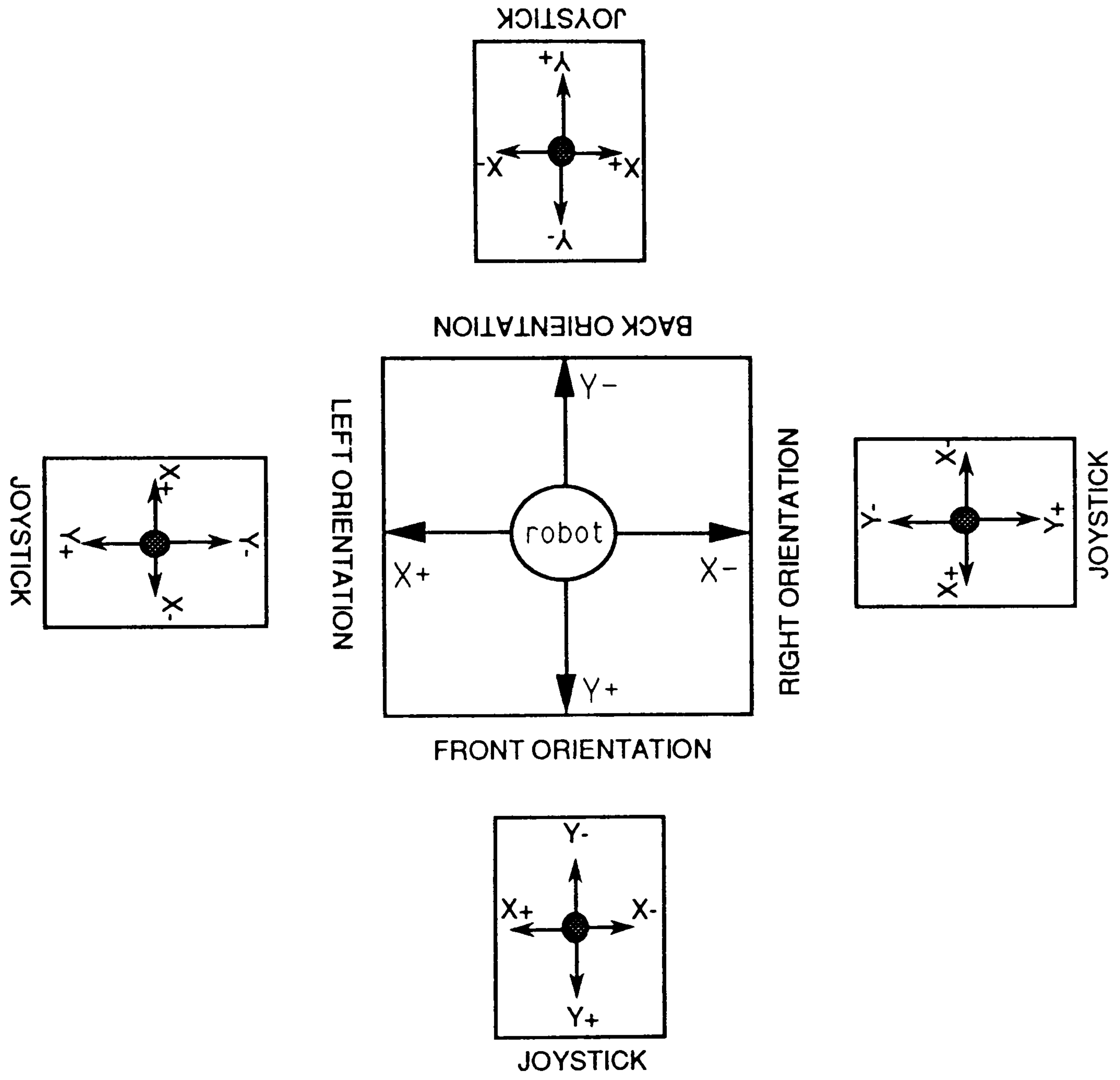


alter this relationship. For example, in world mode programming, joystick movement exactly matches the direction of robot movement along the X and Y axes when viewed from the front orientation (as previously shown in Figure 3.12 and discussed in section 3.5.2). However, when the robot is viewed from any other orientation, joystick movement no longer matches the corresponding robot movements along the X and Y axes and may in some cases be reversed (see Figure 4.13). Thus, the operator may be tempted to move the control in accordance with the direction of intended robot movement in the real world regardless of their understanding of what the actual movement is and which is the appropriate control to achieve that move. In this case, when positioned at the side of the robot, they could make the mistake of moving the joystick forward or back which would result in the robot moving along the Y axis instead of the X axis in accordance with the expected direction of robot movement.

It could be argued that operators might learn to expect robot motion to appear to be different when viewed from alternative orientations and hence would compensate for this in their use of the teach controls. They will know that they have changed their orientation to the robot, due to knowledge of their own physical movement and from cues provided by changes in the field of view (e.g. in Figure 4.10, the image of the robot from the back orientation also shows the robot motor which could not be seen from the front orientation). If this is the case, the operator may not make control selections on the basis of the appearance of the movement from their new orientation (i.e the back), but will perform some kind of 'transformation' of the information so that it is in accordance with the appearance of that movement when viewed from the front orientation. For example, for the situation shown in Figure 4.13, when the operator is at the back of the robot and wishes to move the Tool Centre Point to the left, they may 'imagine' that movement as it would appear from the front orientation - to the right - and make their control selection on this basis.

The principles of control-motion compatibility have already been described in section 3.5.3, and it was stated that the general principle is that controls should move in the same direction as the display movement that they produce. It has been shown that, due to changes in

Figure 4.13 Changes in control-motion compatibility when using the joystick to control world mode movement from alternative human-robot orientations



robot status, consistent and universal control-motion compatibility is impossible to achieve in most programming situations, and it is the individual operator's perception of control-motion compatibility that may determine the basis on which control selection is made. Meeting the requirements of control-motion compatibility is therefore subject to the operator's understanding of the motion reversals that may occur during programming and it is this aspect of the motion control task which seems to have been unexplored within the literature.

4.4.4 Teach pendant design

It has been shown in section 3.5 that variation in teach pendant design produces differences in control-motion compatibility, and that this may influence reliable use of some controls when conditions of robot status are altered. Furthermore, it has also been seen that there arises the potential for a programmer to alternate frequently between different robot systems, each with different teach pendant designs, that has instigated the call for standardisation in teach pendant design.

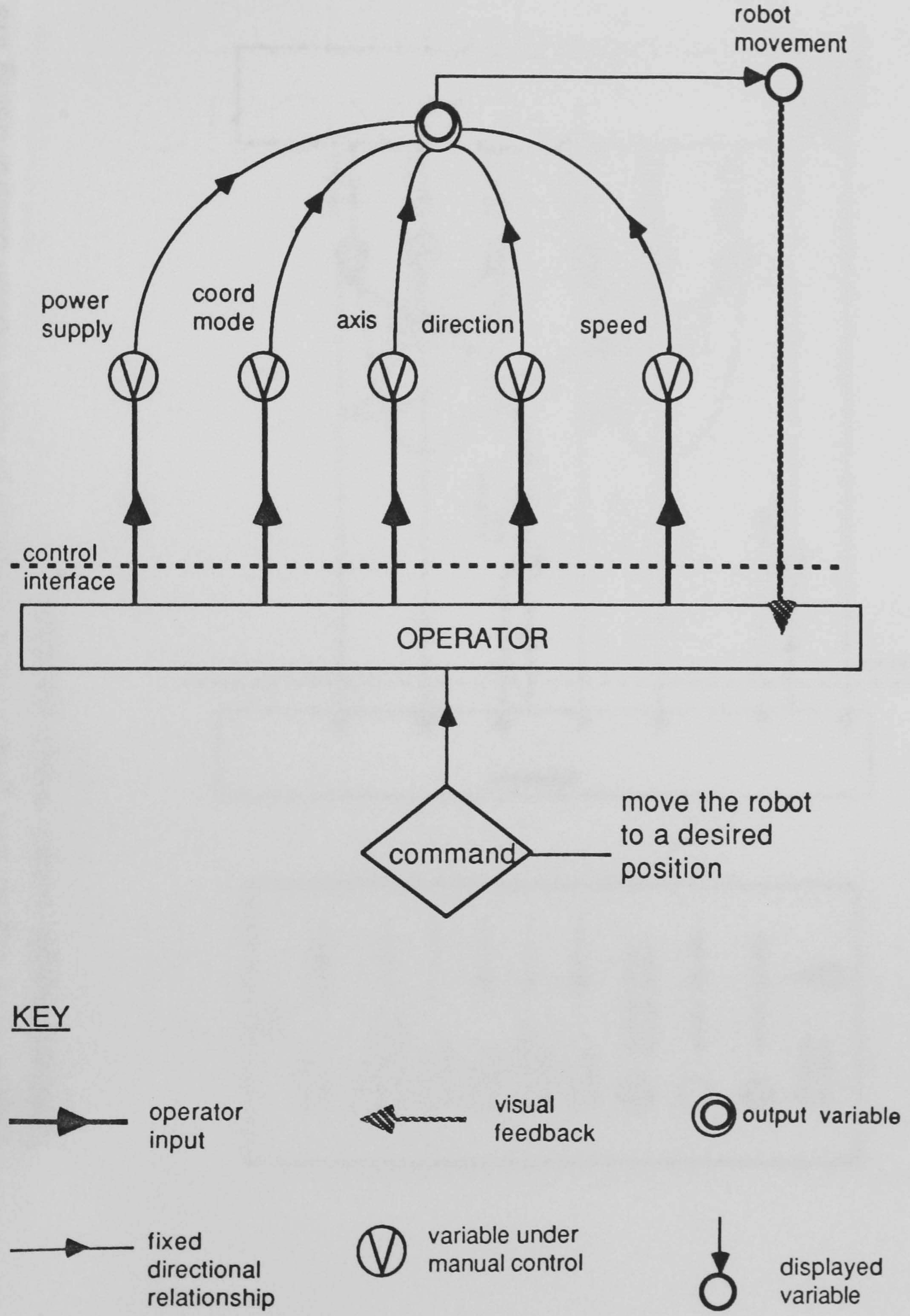
One of the first areas of consideration in this research was a detailed theoretical examination of the process of robot motion control using different teach pendants to determine why one design might be more difficult to use accurately than another. The technique of signal flow graph analysis was applied to represent the motion control process using several teach pendants.

Signal flow graph analysis is a technique developed by electrical engineers to represent feedback in electrical systems (Mason, 1953). It is a procedure which identifies the important variables in a system and enables relationships between these variables to be set out in detail. It has since been adapted to include the organisation of control functions in a system and the interaction of a human operator within the control loop (Beishon, 1967; Sinclair et al, 1966). The signal flow graph is derived by breaking the control process into its constituent parts of input variables, machine controls, output variables, and information feedback channels. The input variables for robot motion control were identified during the task analysis discussed in section 4.1 and shown in Figure 4.2. These input variables were found to be common to all robot teach pendants although the number, design and complexity of the motion controls used to operate them varies considerably between different pendants. In section 4.2 it was shown that for the given command to move the robot from A to B, the programmer selects and activates the appropriate combination of input variables; this is the control input. These controls determine the way in which the robot moves; thus robot movement is the output variable. The programmer receives feedback of his control input by observing the actual movement that the robot makes via the visual information channel. It seemed then that the signal flow graph technique might be an appropriate means of analysis and comparison of teach pendant operations, and is shown in Figure 4.14 for the motion control process.

In general terms, it can be seen that robot motion control requires five input variables and produces one source of feedback. For a comparison of different teach pendants, the technique was applied in more detail. Two examples of the signal flow graph interpretation of this process are shown in Figures 4.15 and 4.16. At this level of detail, it can be seen that there is a much larger number of feedback channels that may be utilised. These examples demonstrate the variation between teach pendants and it was hoped that some measure of decision complexity could be derived from these graphs.

Unfortunately, whilst the signal flow graph technique provides graphical representation of motion control variation between teach pendant designs, the power of the technique lies in its quantitative analysis (Divieti, 1964: Scott, 1986). Therefore, it is more usually applied to evaluation of process control (Beishon, 1967; Sinclair et al, 1966) in which the operator intervenes whenever necessary but is not a constant part of the system. In this respect the signal flow graph is used to assess how the non-permanent control factors (i.e. the human operator) interacts with the permanent control system. The purpose of signal flow graph analysis is, as described by Crossman (1964); " to discover precisely what modes of control are available to the operator and what effects they have over time; to enable the effects of possible or proposed changes in the system to be evaluated in terms of control efficiency and speed...[and] to pinpoint any shortcomings in the flow of information to and from the operator." (p. 3). In order to use this technique correctly for teach pendant evaluation quantitative data on error probability at each input would be required. However, data could not

Figure 4.14 Signal flow graph representation of the robot motion control process



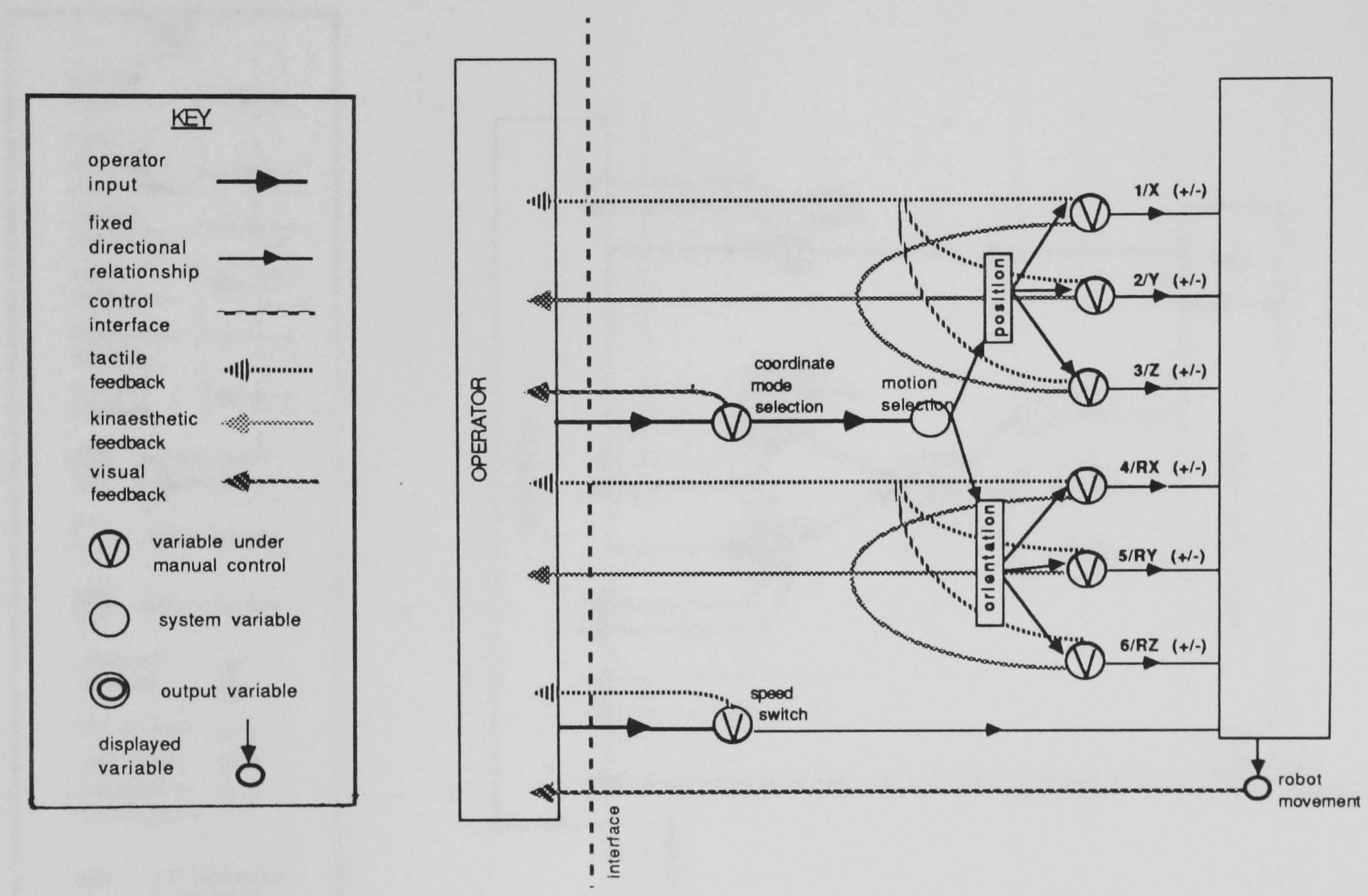
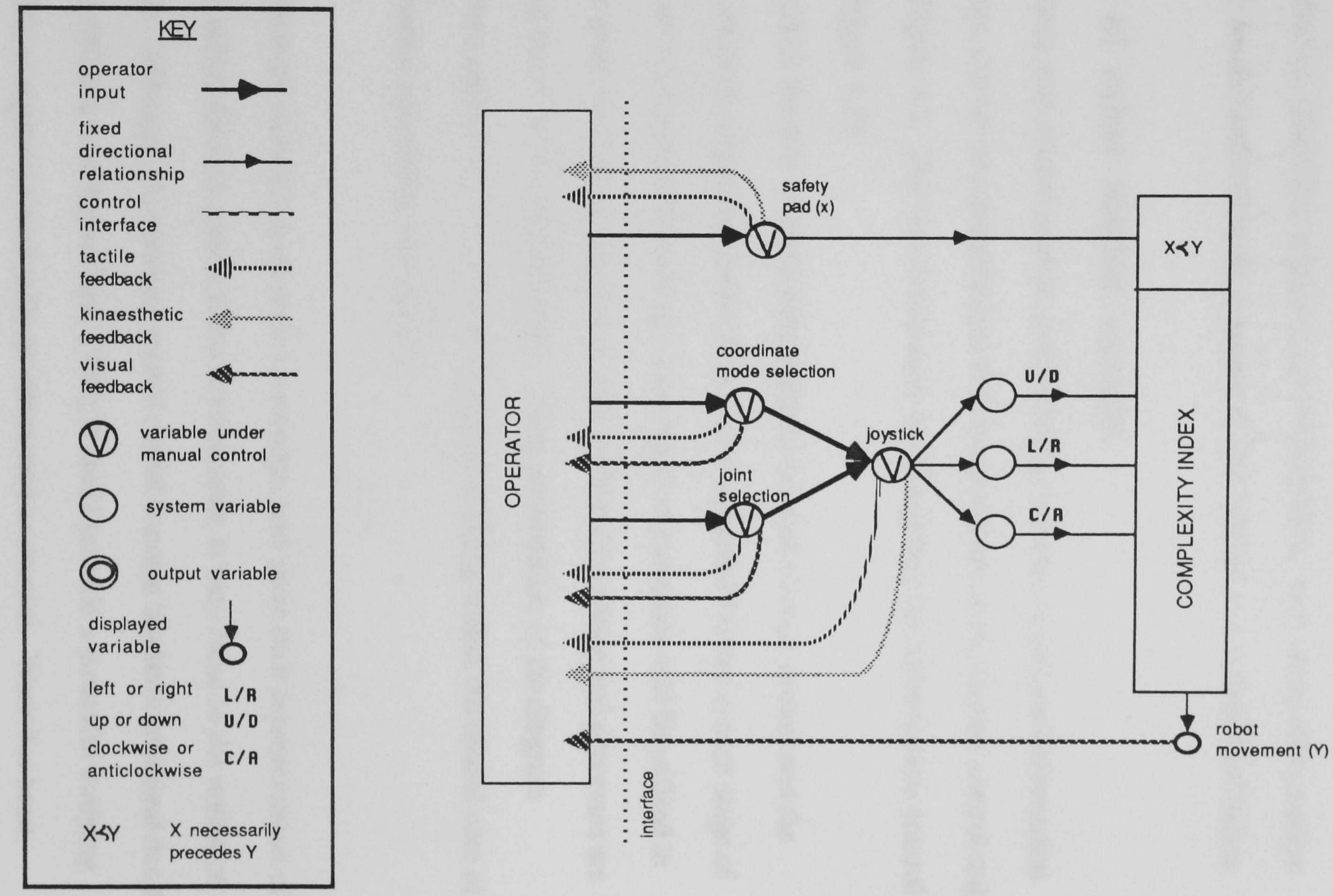


Figure 4.15 Signal flow graph representation of robot motion control using the Unimate toggle-switch teach pendant

Figure 4.16 Signal flow graph representation of robot motion control using the ASEA joystick teach pendant



be obtained at this stage of the research work since there was no means of accurately recording the errors. Thus it was decided that despite a certain attractiveness, the application of signal flow graph analysis was not practical for this research work. Moreover, it was at this stage that a decision was made that a laboratory experimental approach would be more useful than a theoretical, albeit qualitative, modelling approach to understanding more about robot motion control. A framework for this experimental programme was needed and is described below.

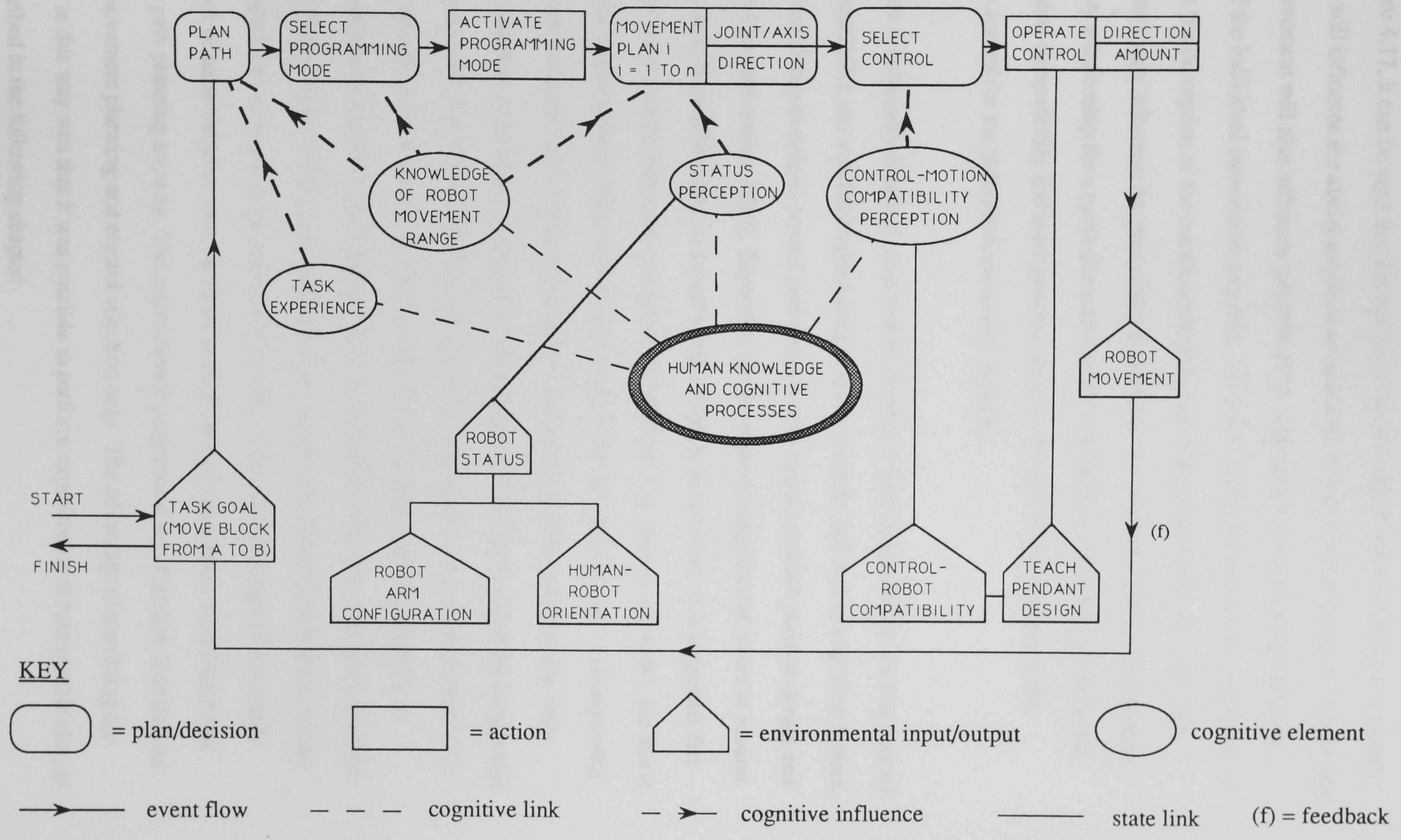
4.5 Framework of robot motion control

Factors of robot status and control-motion compatibility, and their associated information processing requirements, can be incorporated into the representation of the motion control task previously shown in Figure 4.5. The new framework for describing the robot motion control process is shown in Figure 4.17.

This diagram illustrates the role of the human operator in robot motion control and the assumed relationships between cognitive elements and environmental factors at each stage of the control task. Human resources of knowledge and cognitive processes will be utilised in completion of the task goal; the relevant aspects of such human knowledge and processes are drawn out in "exploded form" in the representation. Thus, all elements in the diagram connected by dotted lines with no arrows are to be regarded as being within the central core of knowledge and information processing capabilities.

The idea of the operators' drawing upon their knowledge, and upon their representation of their knowledge of the robot, the task goal and the environment, is very close to the notion of operator mental models. Although the operator mental model concept has been criticised due to overuse or even abuse (Wilson and Rutherford, 1989), it could provide a powerful unifying framework within which to represent such tasks as robot motion control. Work has been underway to develop methods with which to identify mental models of manufacturing processes such as robot systems (Wilson and Rutherford, 1988). However, many criticisms can be levelled at methods reported in the literature (Rutherford and Wilson, 1991). Consequently, the mental models approach has not been adopted for the present research work.

Figure 4.17 Framework of the robot motion control process



In Figure 4.17, it can be seen that the operators' knowledge of robot movement and their experience will influence the ability to plan a suitable path to achieve the task goal. Knowledge of robot movement will also influence selection of an appropriate programming mode and planning of the individual movements required. For each individual movement, perception of robot status (i.e perception of the combination of human-robot orientation and robot arm-configuration), may influence the plan of that movement. Perception of the control-motion compatibility relationship for a particular teach pendant (influenced obviously by the actual control-motion compatibility and teach pendant design) will determine selection of the appropriate control for the individual movement required.

These are theoretically assumed relationships between robot system factors such as control-motion compatibility and conditions producing motion reversals, and human cognition factors. Previous research has examined control performance with respect to teach pendant design and control selection (see section 2.2.3). However, the framework suggests that errors in motion control may arise from difficulties at a much earlier stage in the process. It is suggested that robot system factors might add to the complexity of the task (e.g. motion reversals), but that it is the operator’s perception of these factors which will influence performance. Consequently, the framework forms the basis of the experimental approach undertaken during this work. This was to examine some of the relationships identified in the framework in order to ascertain their effects on control performance. However, as was mentioned at the outset (section 1.1), the author's specific area of interest in robot motion control is performance reliability in individual movement control, rather than in planning and mode selection. Therefore, the first three stages of the motion control task (path planning, mode selection and activation), whilst important, were not evaluated in the experimental work. This enabled usage of the readily available pool of naive subjects who, by virtue of their lack of experience, would have had difficulty in path planning anyway. The experimental programme was therefore focussed on individual movement planning and control selection only. The advantage of restricting the control task in this way was that it was possible to perform experiments of manageable size, as will be described in the following chapter.

CHAPTER 5 - EXPERIMENTAL METHODOLOGY

CHAPTER 5: EXPERIMENTAL METHODOLOGY

5.1 Experimental Objectives

In the previous chapter, the human factors identified as having a potentially major influence in the planning and execution of robot motion control are the observer's/operator's perception of robot status and their perception of control-motion compatibility. It has been proposed that the effect of changes in robot status may be to confuse the operator in their planning of the appropriate robot movement required to achieve a given change in robot position. On this basis they may then activate the wrong control on the teach pendant. This raises an important question for research of teach pendant usability;

Do robot motion control errors result from poor control design *per se*, or from the operator's inability to consistently translate movement plans into individual robot movements and into the correct activation of the robot teach control?

The implications of this question are that research should be directed towards addressing more fundamental perceptual issues in robot motion control, before accurate evaluations of teach pendant designs can be made and therefore before standardisation can be achieved. Thus, the experimental questions addressed in this present research were;

1. How do observers perceive robot movement?
2. Do changes in human-robot orientation affect perception of robot movement?
3. Do changes in robot arm-configuration affect perception of robot movement?
4. Does perception of robot movement affect teach control usability?

Further questions of interest to robot system design or implementation and user training were;

5. Are these effects different between joint and world programming modes?
6. Are these effects different between toggle-switch and joystick control designs?

5.2 Experimental methodology

In order to examine the questions posed above, an experimental programme was developed which was divided into three general stages covering different aspects of the motion control process. Whilst being adequate for the experimental requirements, the methodology developed during each experimental stage was partly governed by restricted resources, especially in the earlier stages, both in terms of technical support and equipment availability. The general experimental stages may be classified as:

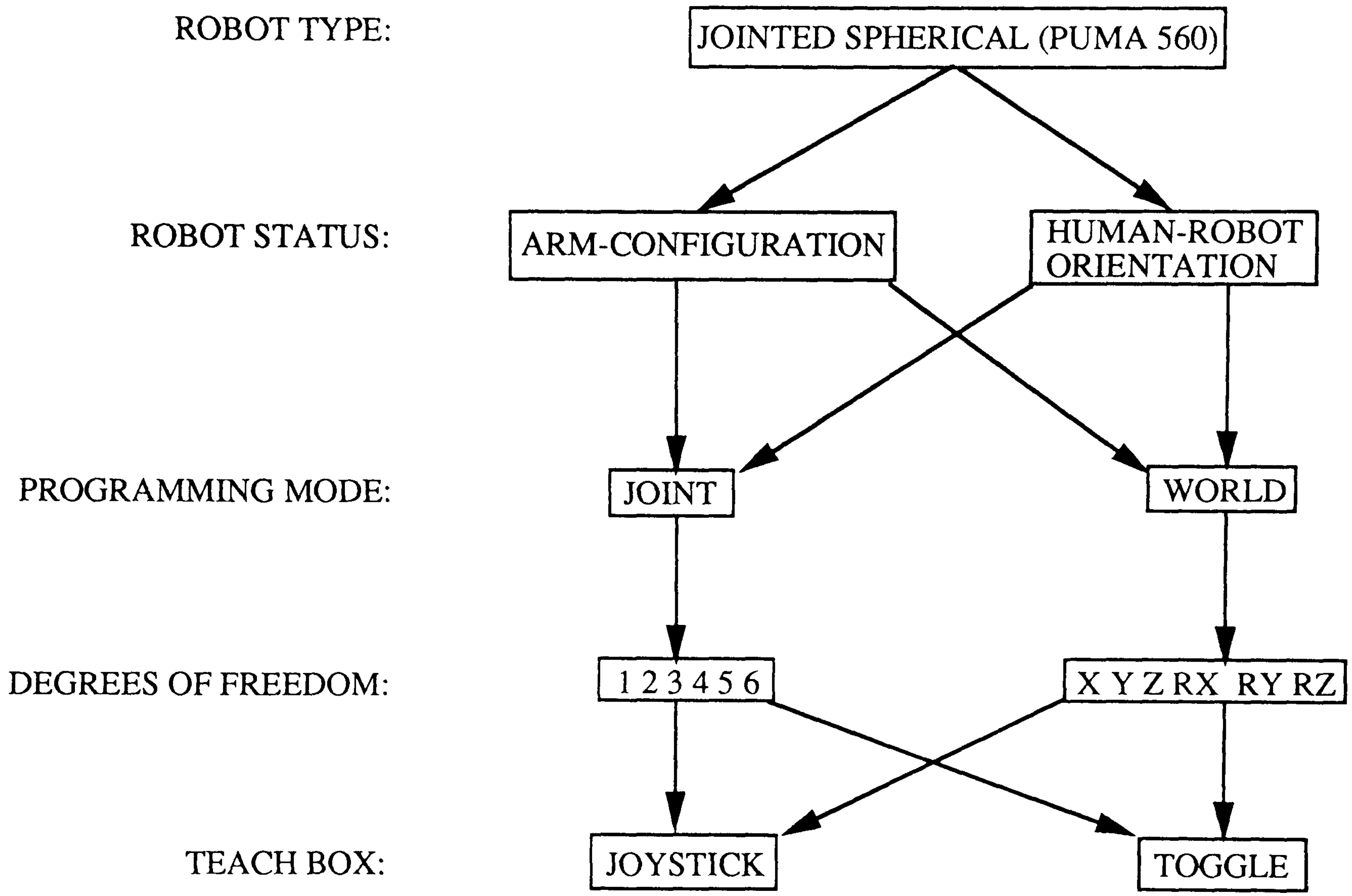
1. Perception of robot movement
2. Control-motion compatibility
3. Control performance with motion feedback

As previously mentioned, it was desirable to limit the variables in each experiment and so the variables of interest are shown in Figure 5.1. It should be noted that these represent only a part of the total combination of variables encompassed generally in robot teach control; only one robot type was used for the experiments, only the joint and world modes of programming were examined and only two teach pendant designs were used.

Clearly there were limits on the equipment available to the author but the PUMA 560 robot offered ease of programming and interfacing facilities as well as the versatility of movement provided by a jointed spherical type robot (described in section 3.1.4.1). The latter advantage enabled an examination of the effects of robot arm-configuration in the experiments. The experiments did not consider the tool mode of programming because it was thought that the possible reversals in the control-motion relationship within this mode would be too complicated for naive subjects. In respect of the teach controls, it has already been mentioned (in section 3.4) that the joystick and toggle-switch teach boxes were used in the experiments because they represent the two main types of teach pendant design examined by other researchers and that they were more readily available to the author than other types.

The methodology for each experimental stage and the experimental variables examined in each are summarised below.

Figure 5.1 Possible combinations of the experimental variables in robot motion control



5.2.1 Stage 1: Perception of robot movement

Stage 1 of the programme was aimed at assessing subjects' comprehension of the robot's range of movements and of changes in robot arm-configuration. The experimental variables examined are shown in Figure 5.2. In this stage only arm-configuration was examined because the experimental set-up did not allow access to all sides of the robot. Thus, the subject was seated at the front of the robot and performed the experimental task in each of four arm-configuration positions (described in detail in section 5.3.2). Only the joint mode of programming was examined in this stage because the reversals in the control-motion relationship are produced by changes in arm-configuration for individual joint movements (as has already been discussed in section 4.4.2.2). Arm-configuration changes do not produce reversals in the control-motion relationship for world mode movements.

The experiments in this stage considered a part of the robot motion control process, previously illustrated in Figure 4.17. Figure 5.3 shows the relevant section of the framework examined in these experiments but it should be noted that the subjects were not required to plan the individual movements as these were provided. Instead, they were asked to describe each movement presented in terms of joint and direction of movement. Therefore, these experiments relied upon using the subjects' verbal description of what they saw to provide information about the perceptual difficulties that may arise from changes in robot arm-configuration.

5.2.2 Stage 2: Perception of control-motion compatibility

Stage 2 of the experimental programme examined the expectations of control compatibility using the two control designs (joystick and toggle-switch pendants) described in section 3.4.

This time the robot arm-configuration remained constant but the subjects were positioned at four different orientations to the robot (front, right, left and back). This was made possible because the experimental set-up had been altered to enable access to all four sides of the robot. Two experiments were performed in order to examine these effects in both JOINT and WORLD programming modes. Only the main degrees of freedom were used in each experiment (joints 1,2 and 3; axes X, Y and Z). This was for two reasons; they represent

Figure 5.2 Experimental variables used in stage 1

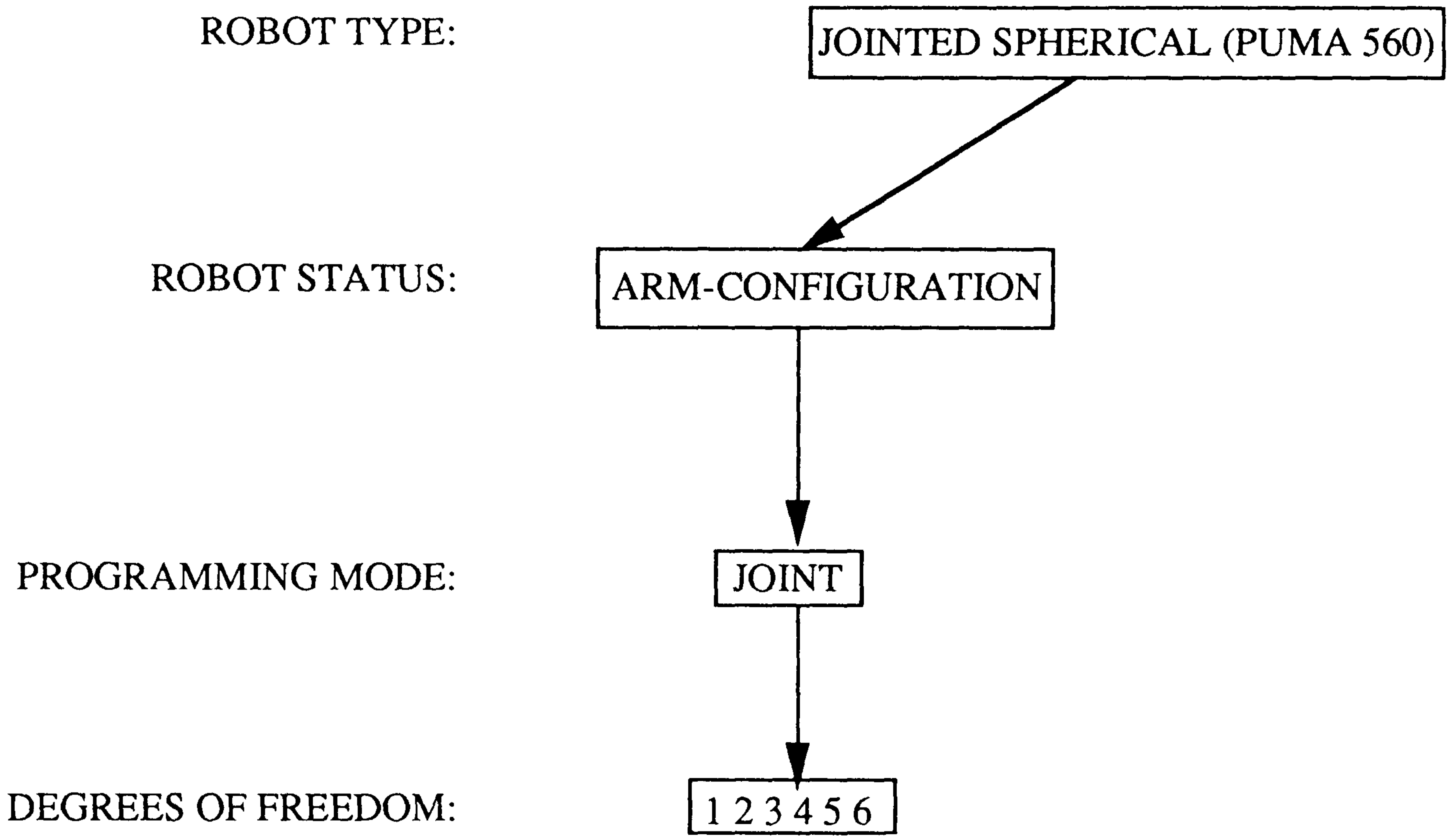
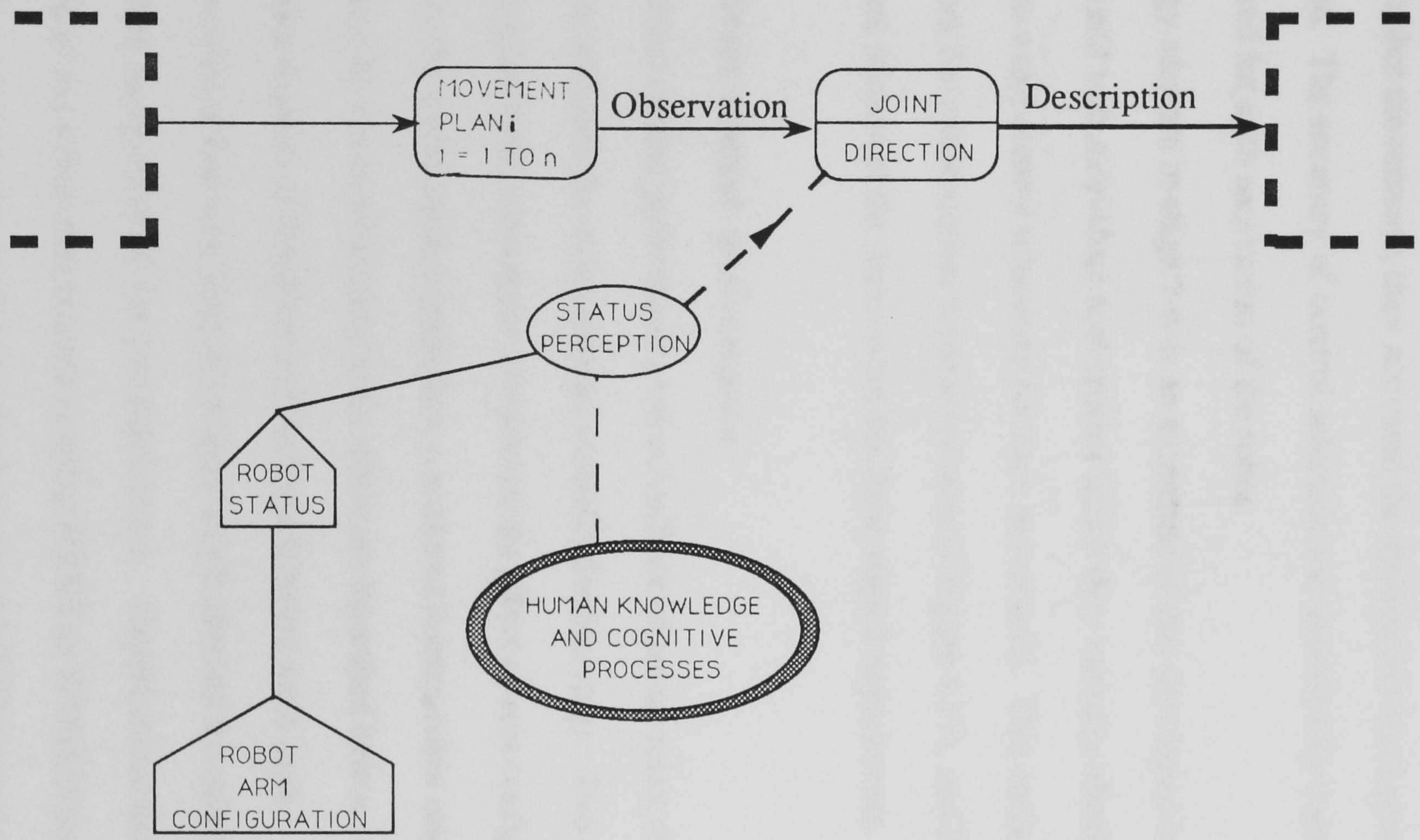


Figure 5.3 Relevant section of the motion control framework examined in experimental stage 1



ADDITIONAL KEY

→ Experimental task

gross arm movements and the experimental design was simplified. Figure 5.4 shows the variables examined in these experiments.

At this stage, it was not yet possible to interface the teach pendants to the robot itself, although it was possible to record the control selections made via a micro-computer interfaced to the teach boxes. Therefore, the experimental method used in this stage involved the subjects responding to fixed robot movements; they activated the appropriate teach pendant control after the robot had moved. The accuracy of control selection was assessed by comparison with the actual control required for each movement of the robot.

The methodology adopted in stage 2 was an extension of that developed in stage 1 (i.e. the subjects were presented with individual movements which they verbally identified, and they were also required to make control selections for each movement). This encompassed a further part of the framework for robot motion control (as seen in Figure 4.17), and Figure 5.5 illustrates the relevant section of the framework for these stage 2 experiments.

5.2.3 Stage 3: Direct control performance

This stage examined control performance when feedback of actual robot motion was provided. Figure 5.6 indicates the experimental variables for this stage. Two experiments were carried out; the joint mode experiment considered the effect of arm-configuration on performance whereas the world mode experiment considered human-robot orientation. The difference was dictated by the experimental tasks which are described below. Again, as in stage 2, only the major degrees of freedom and both teach boxes were used.

An interfacing technique had now been developed which allowed the user to achieve direct control of robot motion using either of the two teach boxes. Experimental tasks were devised that involved a series of individual movements in either JOINT or WORLD programming modes. In the world mode experiment this involved driving the TCP (represented by a pencil placed in the robot gripper) through a 3-Dimensional maze. However, for the joint mode experiment it was not possible to devise a parallel task with such inherently obvious motion requirements as the maze, and so a series of motion instructions were visually presented to the subject in the form of a joint number and direction arrow (e.g. 2 ↑). This set-up prevented

Figure 5.4 Experimental variables used in stage 2

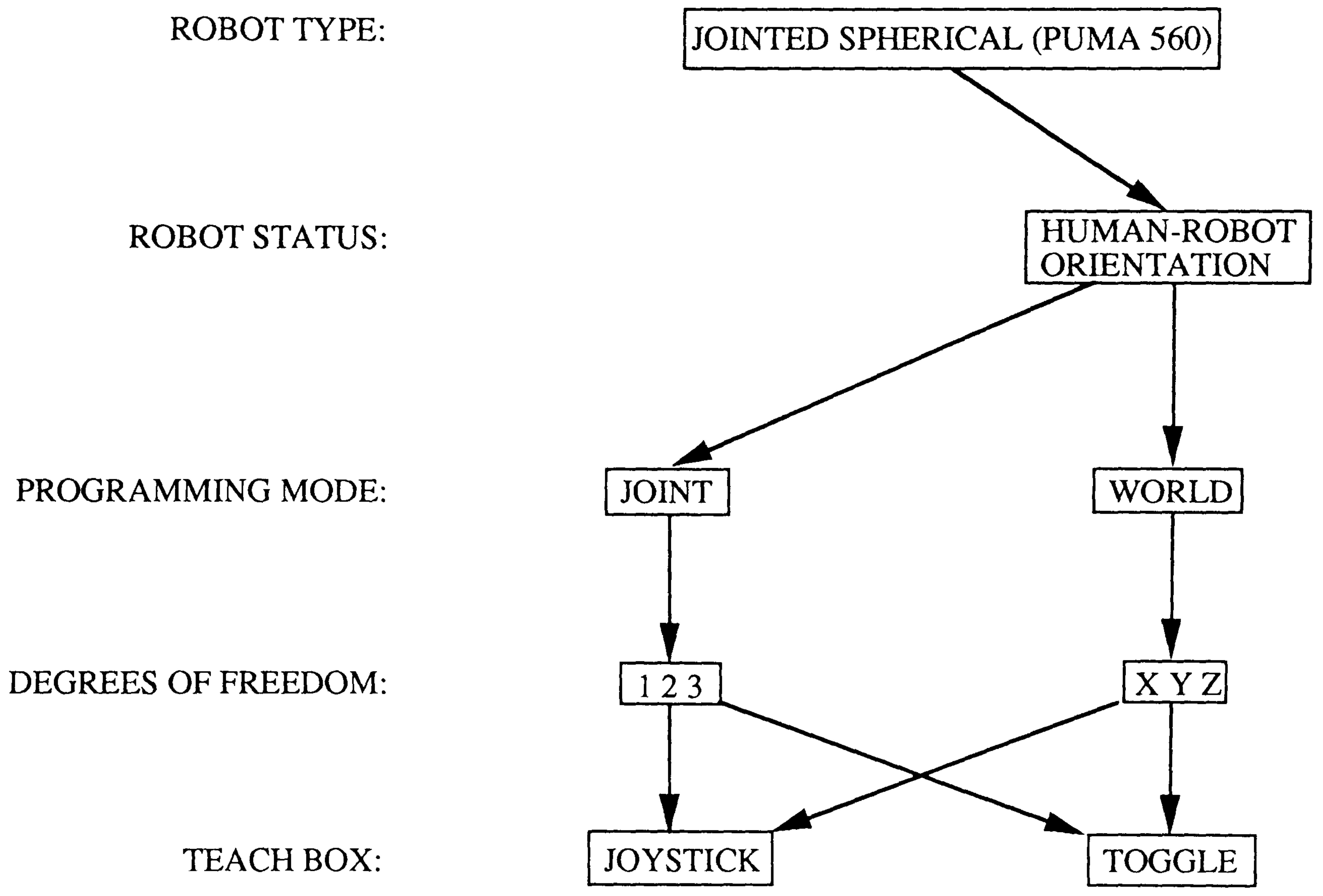
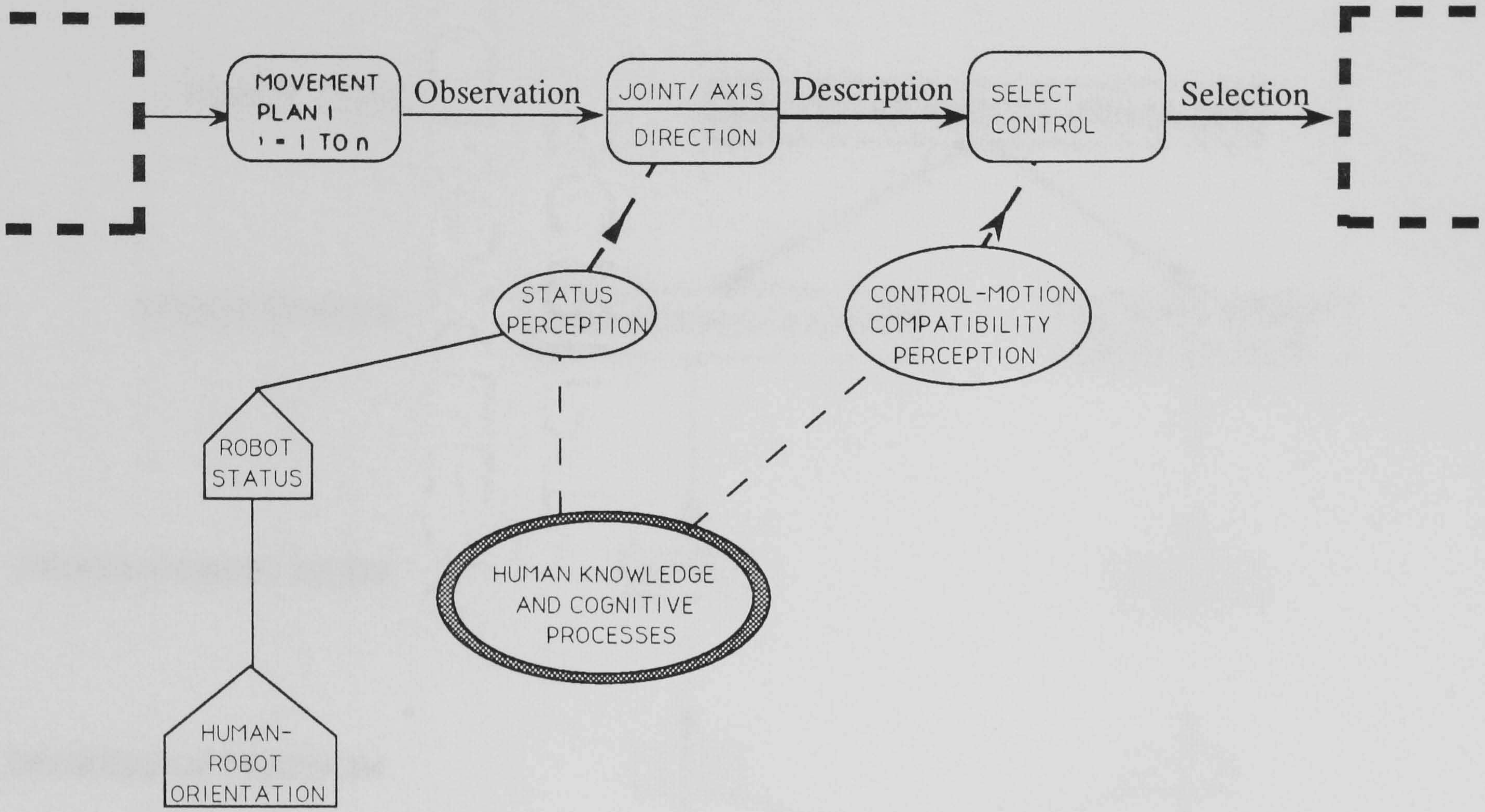


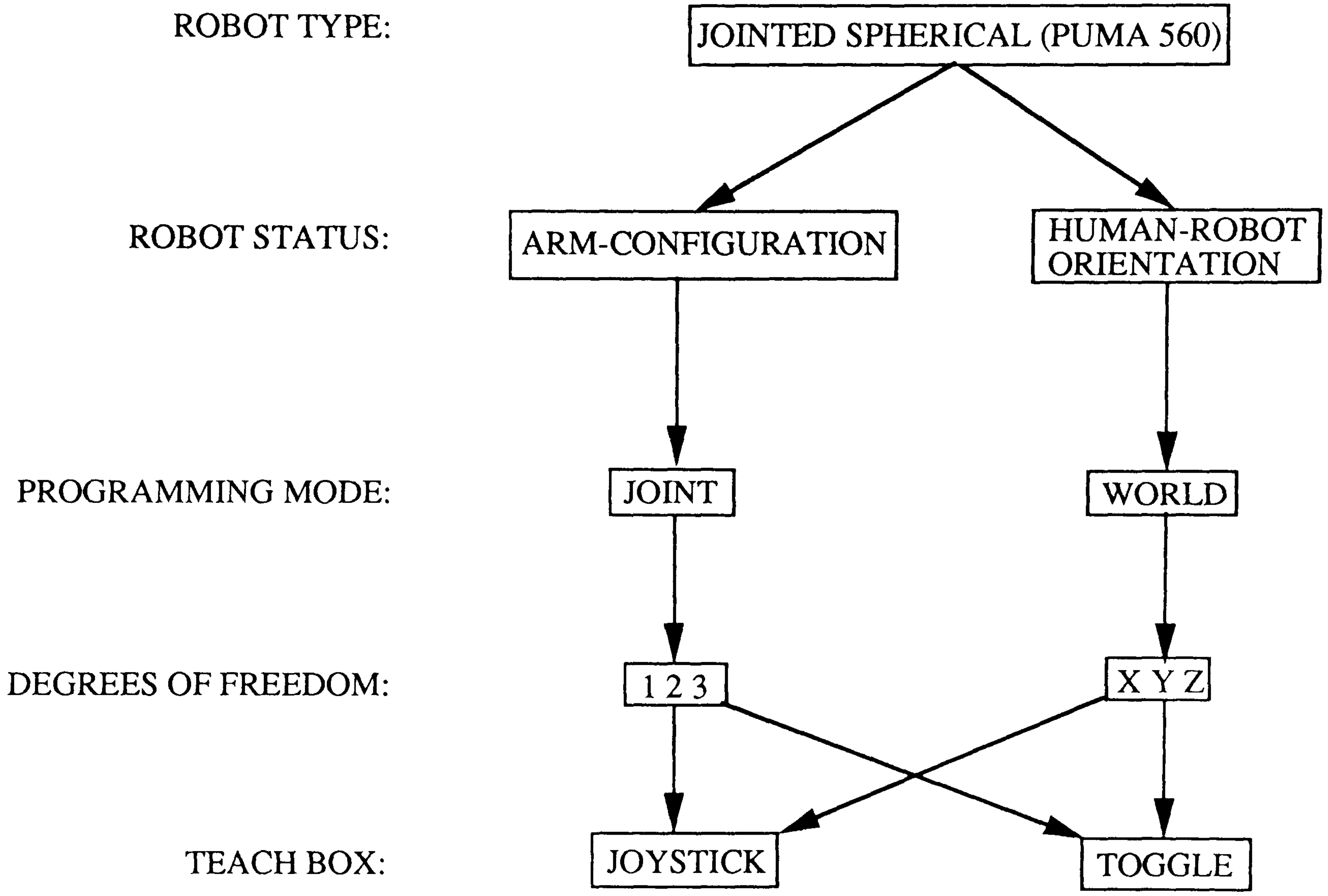
Figure 5.5 Relevant section of the motion control framework examined in experimental stage 2



ADDITIONAL KEY

→ Experimental task

Figure 5.6 Experimental variables used in stage 3



access to different human-robot orientations.

Control performance was measured by the number and type of errors made under different conditions of robot configuration (for JOINT mode) and subject-robot orientation (for WORLD mode).

With this technique, the effect of motion feedback on the control task could be examined. Therefore, the relevant part of the framework for robot motion control for these experiments is as shown in Figure 5.7.

5.3 Experimental equipment

5.3.1 The robot

A Unimate PUMA 560 (Mk 1) anthropomorphic robot was used for all the experiments. This type of robot has six degrees of freedom (individual movements) in each of three programming modes; JOINT, WORLD and TOOL. These modes of programming have already been described in section 3.2.

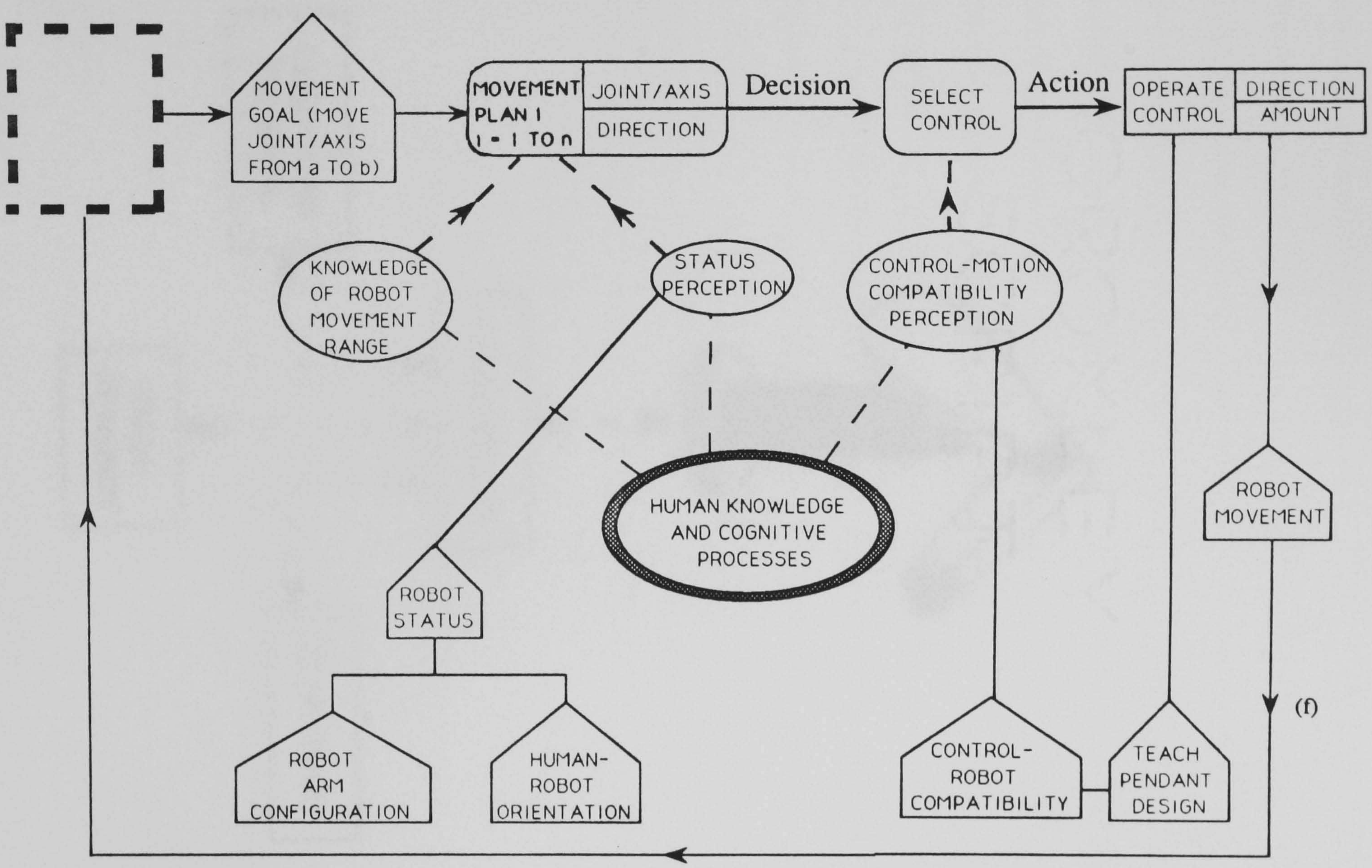
A summary of the robot system is presented below but further details can be obtained from the Unimate PUMA programming manual (Unimation Inc., 1978).

The basic units in the robot system are the controller, software, teach pendant, input/output signals and the robot arm. The controller is the master component of the electrical system; all signals to and from the robot pass through the controller and are used by it to perform real-time calculations to control arm movement and position. The flow of information between the system units and the robot arm are shown in Figure 5.8.

The system software that controls the robot arm is called VAL. This is a high level language which is stored in the computer memory located in the controller. The VAL software interprets the operating instructions for the robot arm and the controller transmits these instructions from the computer memory to the arm.

To teach the arm, either of two procedures may be used. The teach pendant may be used to manually direct the movements of the robot arm through each step of the task. The teach pendant has six toggle-switches relating to the six degrees of freedom. Programming mode is

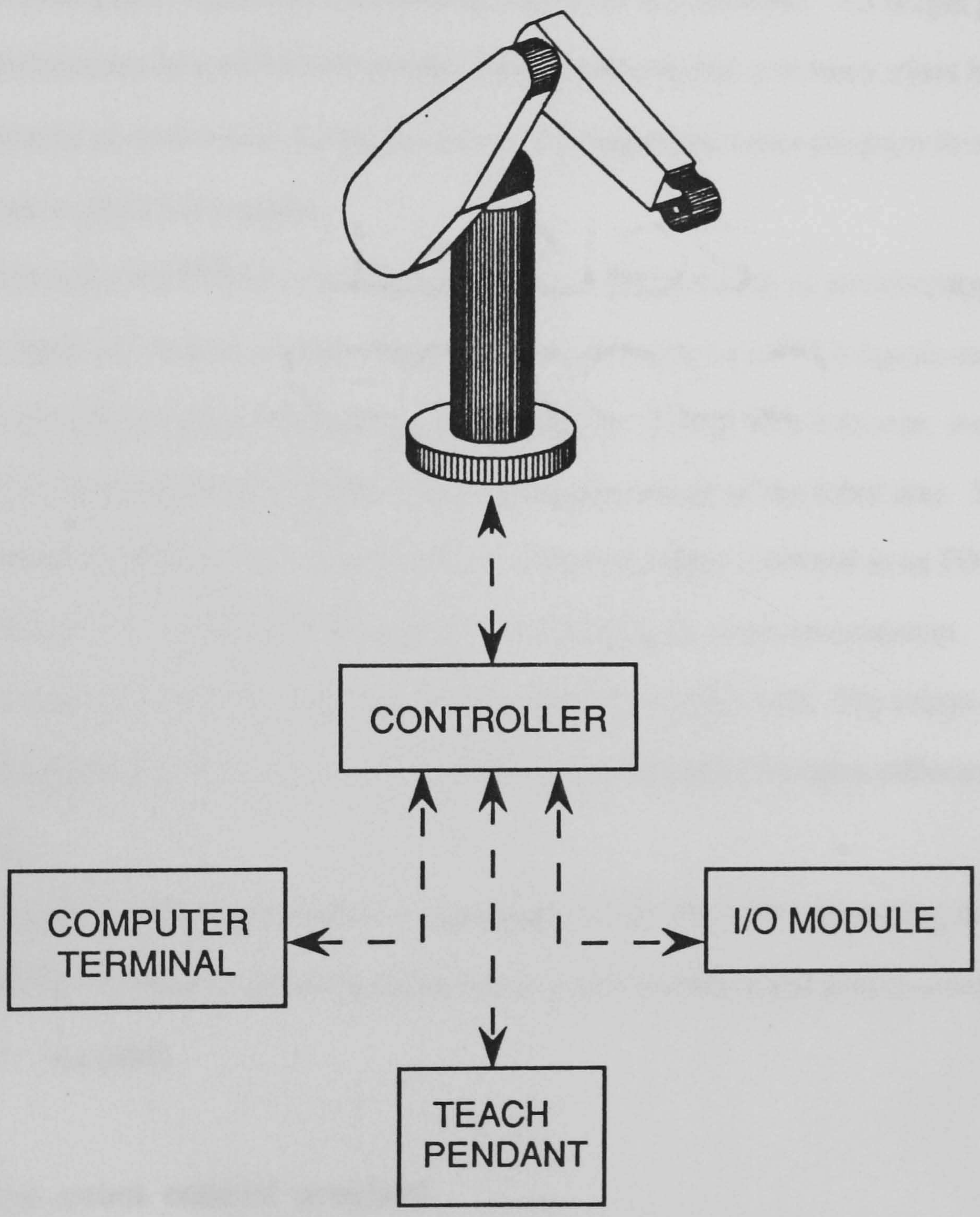
Figure 5.7 Relevant section of the motion control framework examined in experimental stage 3



ADDITIONAL KEY

⟶ Experimental task

Figure 5.8 Information flow within the PUMA system



selected separately and only one mode can be operated at one time This has been discussed in section 3.4.1. These steps are recorded and then stored in the computer memory. The second method is to write a program using VAL instructions. Positional data and VAL programs are entered into the computer memory through the terminal keyboard. In either case, the controller transmits the instructions from the computer memory to the arm. Positional data obtained from incremental encoders and potentiometers in the robot arm are transmitted back to the controller/computer to provide closed-loop control of arm motions. All taught points are stored as transformations in a coordinate system fixed relative to the stationary robot base. Real time computations are performed during the actual running of the robot program to convert the stored data to joint information.

Additionally, the PUMA can be programmed to interact with its environment by using external input and output signals. External input (referred to as WX) signals can be used to initiate a specific program instruction or a subroutine. Using VAL software, these signals are included in the program as conditions and control the action of the robot arm. Signals may be high (voltage applied) or low (zero voltage). External output (referred to as OX) signals allow the PUMA system to control other equipment related to its work environment. These signals operate via the I/O module located at the front of the controller unit. The relays mounted in the I/O module are solid state, optically coupled, and are designed for open collector transfer operation.

Power for the robot joint motors is supplied through the cable connecting the robot arm and the controller. Feedback signals from the incremental encoders and potentiometers are also carried by this cable.

5.3.2 The robot control program

For all the experiments, the robot was programmed to move to specific locations which produced certain configurations (e.g. normal position, rotation and 'flip' changes as shown in Figure 5.9). The ability of the jointed spherical type robot to perform an arm 'flip' motion was previously described in section 3.3. The joint transformations from the (0,0,0) position for each configuration are given in Table 5.1 and shown in Figure 5.10.

Figure 5.9 The PUMA 560 anthropomorphic robot shown in four arm-configuration positions (A, B, C, D). The arrows indicate how each new configuration is derived from the normal position.

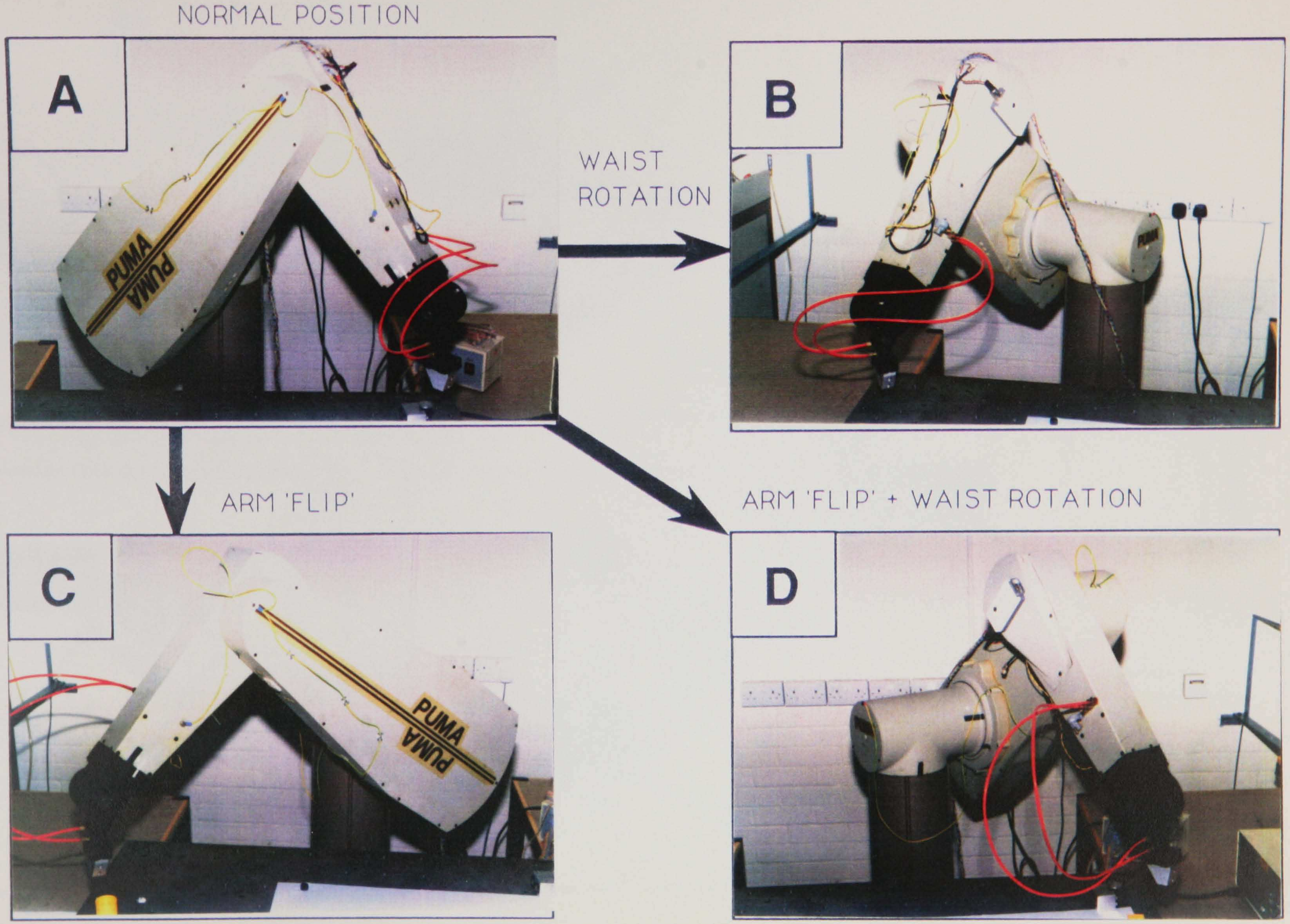


Figure 5.10 Individual joint transformations (from 0,0,0 position) for the four arm-configuration positions (A, B, C, D)

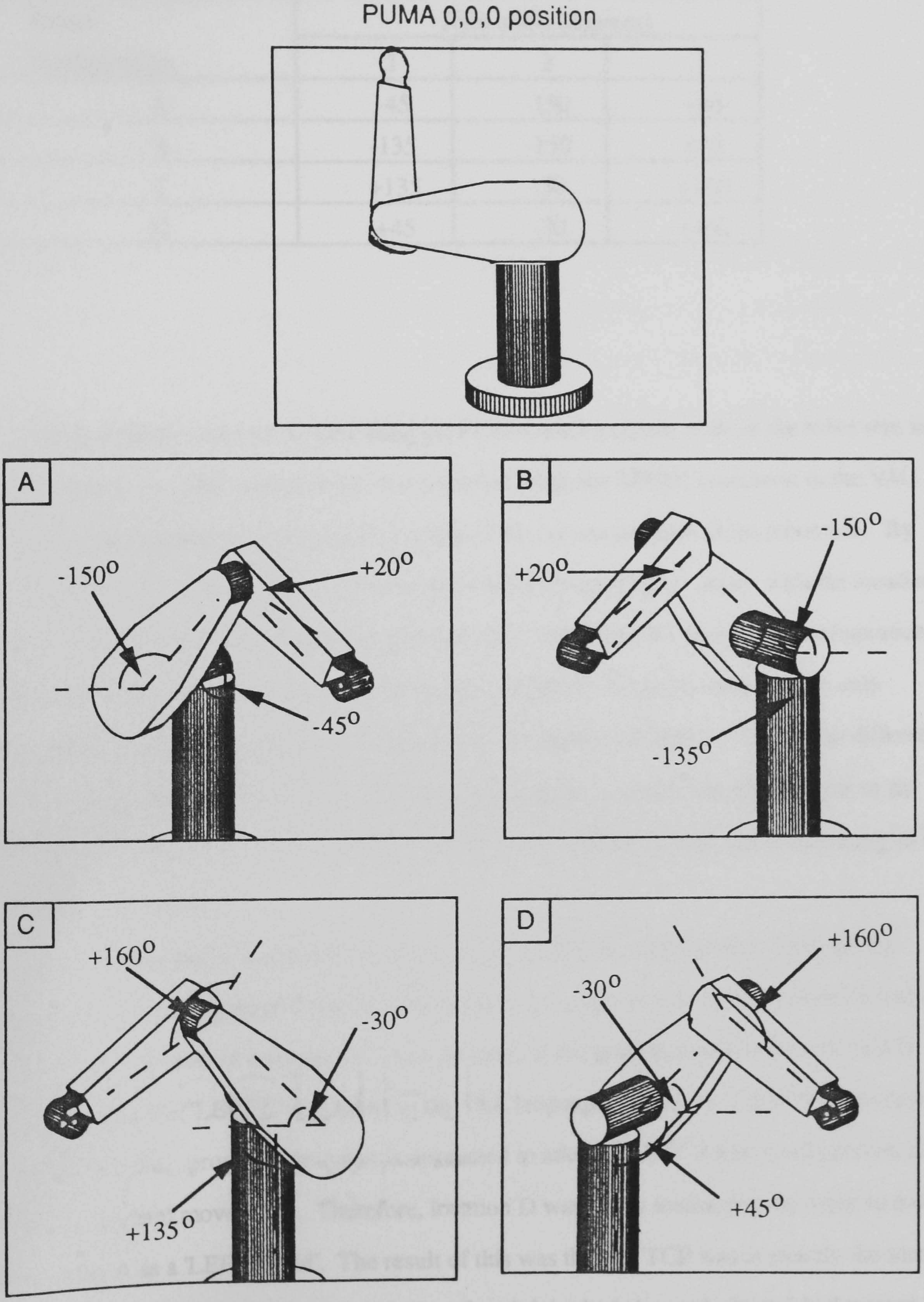


Table 5.1 Joint angles of transformation for each robot arm-configuration

Robot Configuration	Joint angle (degrees)		
	1	2	3
A	-45	-150	+20
B	-135	-150	+20
C	+135	-30	+160
D	+45	-30	+160

These locations were set by first using the PUMA teach pendant to drive the robot arm into configuration A. This configuration was recorded using the 'HERE' command in the VAL programming language to give a location name to the current position of the robot arm. By typing "HERE A" at the terminal, the computer stored the given joint angles with the location name 'A'. Configuration B was set by driving joint 1 90° about the base from configuration A. This configuration was then recorded by typing "HERE B'. It can be seen that the only difference between configurations A and B is the 90° rotation of joint 1. There is no difference in the joint angles for joint 2 and 3. In both configurations A and B, the robot arm is in its 'RIGHTY' configuration (i.e., the arm is working as a 'RIGHT-ARM' and is operating on the right side of the base).

In configurations C and D the robot arm is in its 'LEFTY' configuration although the location of the robot gripper (TCP) is at the same point in space as in configurations B and A respectively. In order to maintain the exact location of the gripper, configurations C and D were set using the "LEFTY" command in the VAL language. When the "LEFTY" command is included in a VAL program, the robot is instructed to adopt a 'LEFT-ARM' configuration for all its subsequent movements. Therefore, location D was set by instructing the robot to move to location A as a 'LEFT-ARM'. The result of this was that the TCP was at exactly the same point in space but the transformation angles of each joint had changed. Joint 1 had rotated 180°

about the base to place joint 2 on the left side of the base instead of the right. Joints 2 and 3 had been moved in the positive direction 120° and 140° respectively to move them from a 'RIGHT-ARM' configuration to a 'LEFT-ARM' configuration. The procedure for setting location C was exactly the same except that the arm was instructed to move to location B as a 'LEFT-ARM'.

In experimental stages 1 and 2, individual joint movements were also programmed. This was done using the 'TEACH-RECORD' function on the teach pendant. The "TEACH" command is typed at the terminal which then initiates the 'TEACH-RECORD' function. A location name is given (e.g. 'S') and the robot is manually driven to the desired location. When the 'RECORD' button on the teach pendant is pressed, the joint angles of the current position are recorded and stored with location name 'S1'. At the next location the name 'S2' is assigned and so on until the 'TEACH-RECORD' function is ended by pressing the 'RETURN' key at the terminal. This procedure was carried out to teach the individual joint movements in each sequence of moves at each configuration For each recorded location only one joint movement was made. The control program consisted of a speed restriction command and then an instruction to move to one of the configurations (A, B, C or D). Individual move instructions followed in the order of the taught locations (e.g., S1 - Sn). This ensured that the robot would move only one joint at a time in the same manner as was taught. In order to allow the subjects sufficient time to observe each move and respond to it, each move instruction was separated by a 'DELAY' command and a 'WAIT' command. The 'DELAY' command instructs the controller to wait for a given time period before carrying out the next instruction. This ensures that the robot stops exactly at the recorded location. The 'WAIT' command instructs the controller to wait for activation of an input signal before carrying out the next instruction. Input signal number 1 was used for this purpose and was activated by a hand held input switch operated by the experimenter. Thus, the experimenter could control the pace of the experiment according to each subject. Examples of the control programs and taught locations are given in Appendix II, In experimental stage 3, robot control programs were used to actually move the robot arm. This was done using the "drive" or "draw" commands which move a specified joint or axis by a specified amount. The program used input signals, taken from the control switches, to determine which joint or axis was to be moved. A continuous loop within the program ensured that a move of the robot would continue until such time as the input signal ceased (i.e. when the control was no longer operated). The control programs for JOINT and WORLD modes are given in Appendix III.

5.3.3 Robot guarding

In order to comply with safety regulations which require that a fixed guard must divide personnel from a robot when it is being operated by a control program, a perimeter guard was fixed around the robot, just outside of its movement range. There was a wall at the back of the robot to which the perimeter guard was attached. This meant that during experimental stage 1 access to all sides of the robot was not available and the subject was seated at the front orientation throughout the experiment (as shown later in Figure 6.1).

In experimental stage 2, access was required to all four sides of the robot and so the robot was moved further away from the wall and the guard was extended around the back of the robot (see Figure 5.11). The effect of this, however, was that the amount of room at the front of the robot was very much restricted. This had unfortunate consequences for the experiments carried out in stage 2 which will be discussed in the next chapter.

In experimental stage 3, the subjects were given direct drive of the robot arm via the experimental teach boxes. As they were not trained programmers, the perimeter guard was considered insufficient to ensure the safety of the subjects under these conditions. A safety cage was therefore erected in place of the perimeter guard. The cage completely enclosed the robot work envelope but had perspex windows fitted at each side for clear viewing of robot motion (see Figure 5.12). Access to the robot work envelope could be achieved by lifting either of the perspex doors at the front and back of the cage. These were interlocked to the emergency stop system which immediately removed motive power to the robot arm when triggered.

Figure 5.11 Robot guarding for experimental stage 2

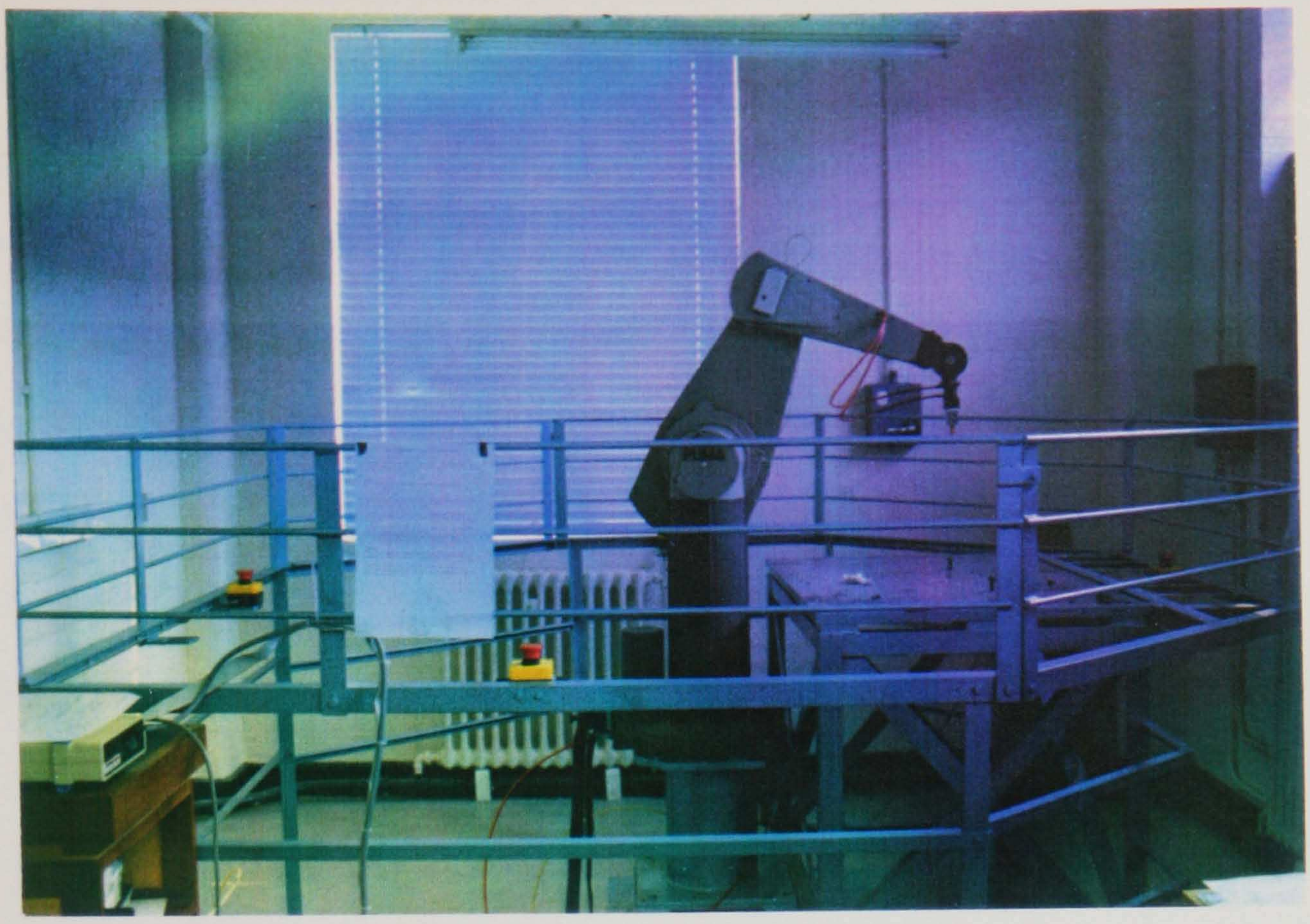
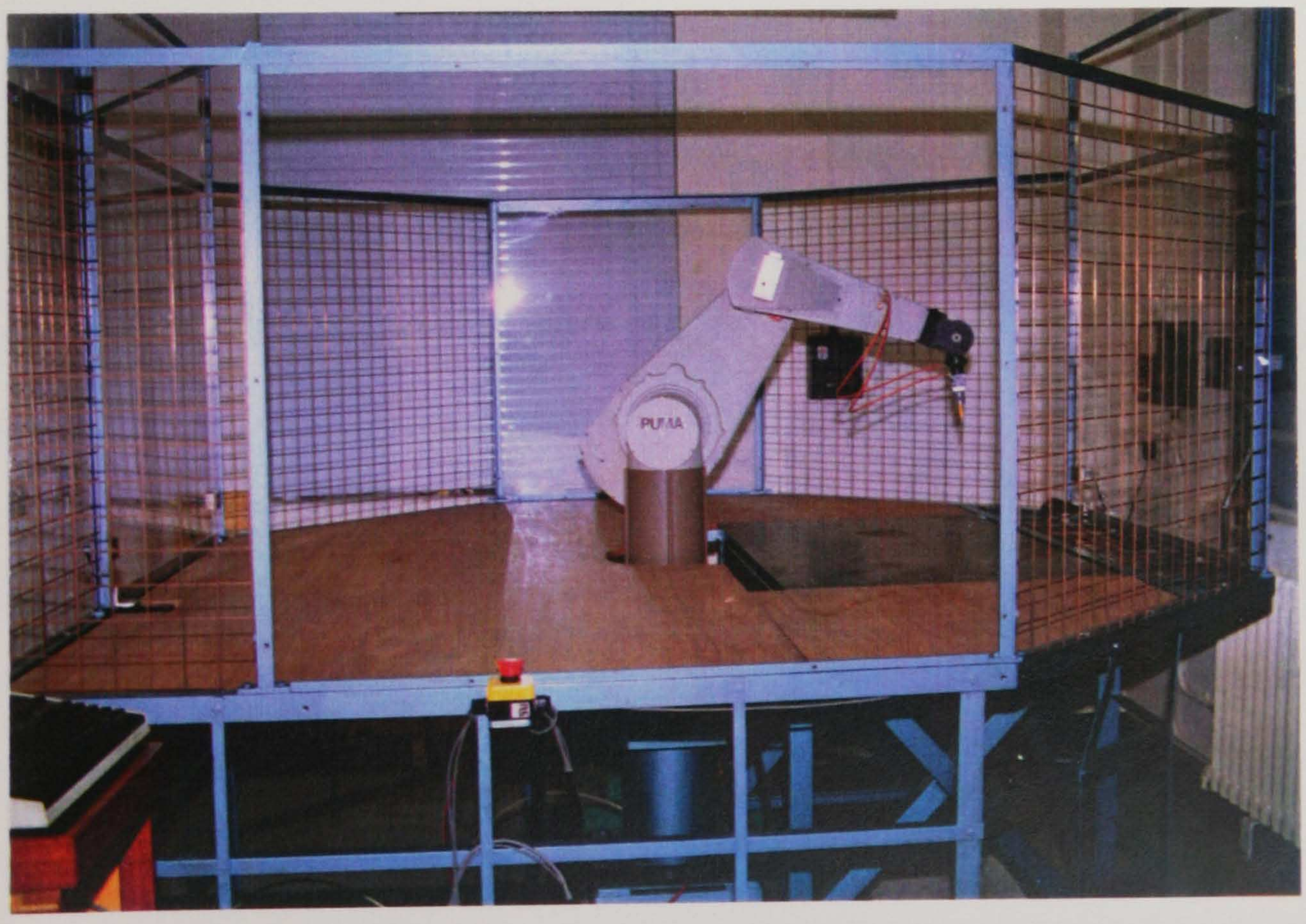


Figure 5.12 Additional guarding for experimental stage 3



5.3.4 Teach controls

It was not possible to use different teach pendants for experimental comparison with the same robot due to the reluctance of the robot manufacturers to impart details of the control-computer interfacing. Therefore, mock-ups of the two types of teach pendants were constructed so that both could be interfaced to the PUMA robot controller. Figure 5.13 shows the mock-up boxes that were made to represent each pendant. In fact this set up provided the opportunity to limit the controls provided on each box to only those relevant to each experiment and so avoid unnecessarily confusing the subjects.

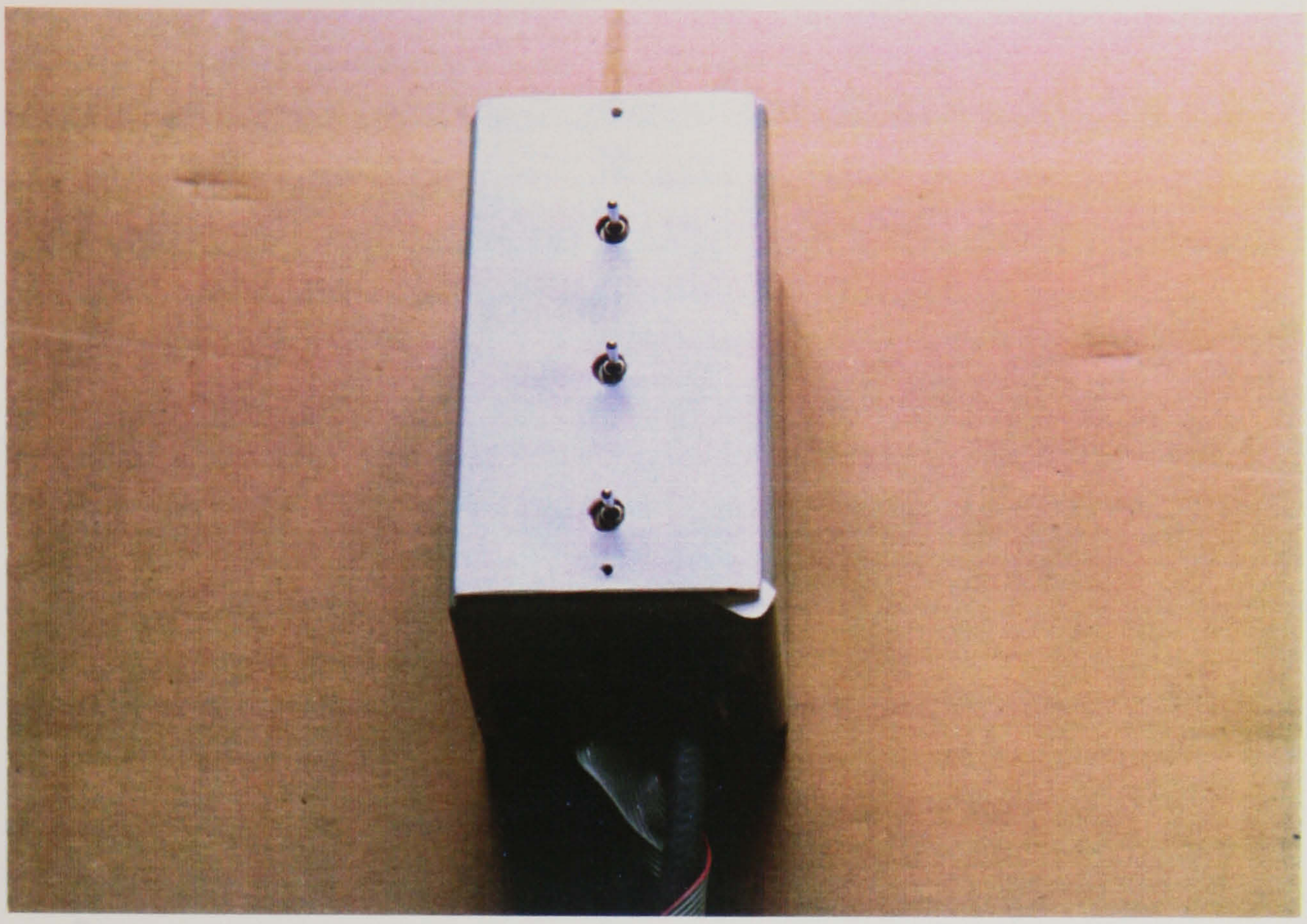
The teach boxes were constructed from plastic boxes (150mm x 77mm x 80mm). Six two-way toggle-switches were equally positioned on one box (as in Figure 5.13a). A 3-axis joystick (Penny and Giles type JS3) was positioned in the middle of the other box (Figure 5.13b). A face-plate was screwed onto the front of each box to indicate control labels. Thus, different face-plates could be used depending on which experiment was being carried out. The faceplate also served to hide the extra controls when not all six were needed. For reasons which will be explained below different teach box labelling was used in experimental stages 2 and 3. It should be remembered that the teach boxes were not used in experimental stage 1.

Experimental stage 2

The faceplates for the two experimental teach boxes are shown in Figure 5.14. It can be seen that for each experiment (i.e. joint or world mode) only the relevant degrees of freedom were marked (i.e. 1,2,3 or X,Y,Z respectively). The toggle-switch pendant was labelled in accordance with the actual PUMA teach pendant (shown previously in Figure 3.7) and the joystick labelling complied with the way in which the ASEA joystick would actually be used (although it must be noted that the actual joystick has no labelling at all, as previously shown in Figure 3.9). At this point it was discovered that the actual labelling for the ASEA joystick was not as had been assumed by Creed (1987), previously discussed in section 3.5. Creed had assumed that the joystick was compatible with robot movement when viewed from the front orientation. All previous examples given in this thesis of the joystick control-robot movement relationship are in accordance with Creed's assumption. However, it was later discovered that

Figure 5.13 Teach control boxes used in experimental stages 1 & 2

a) Mock-up of the Toggle-switch design



b) Mock-up of the Joystick design

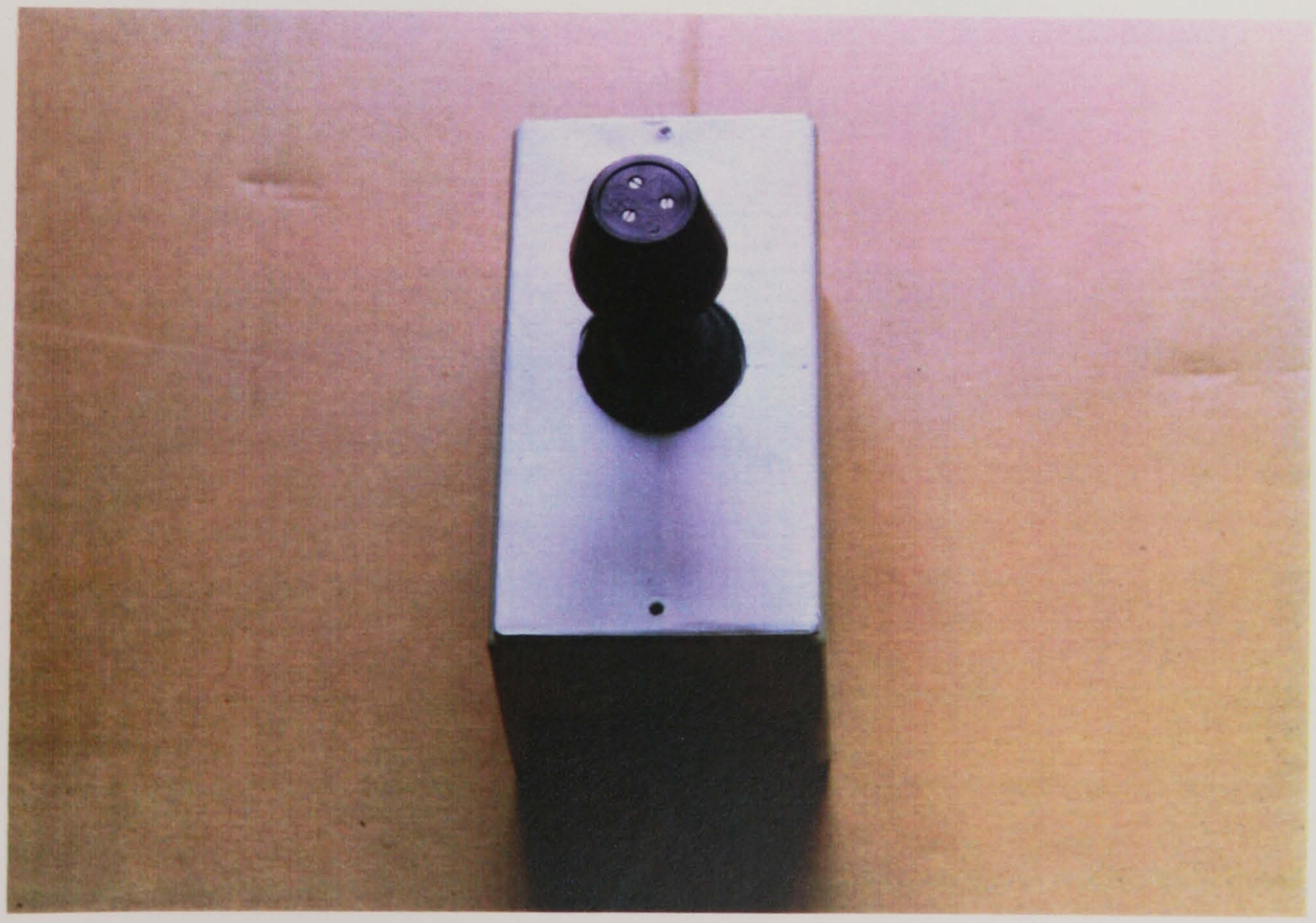
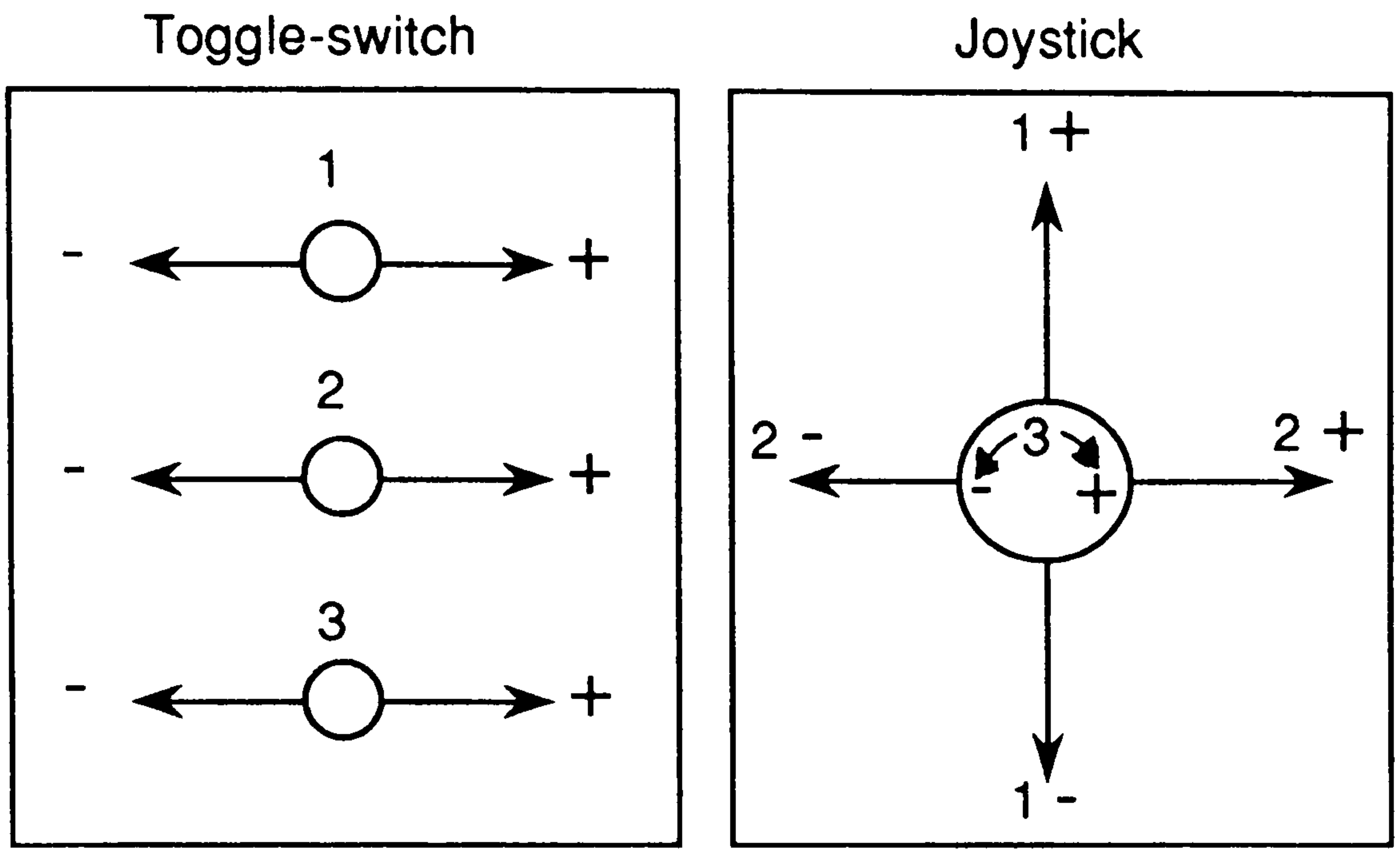


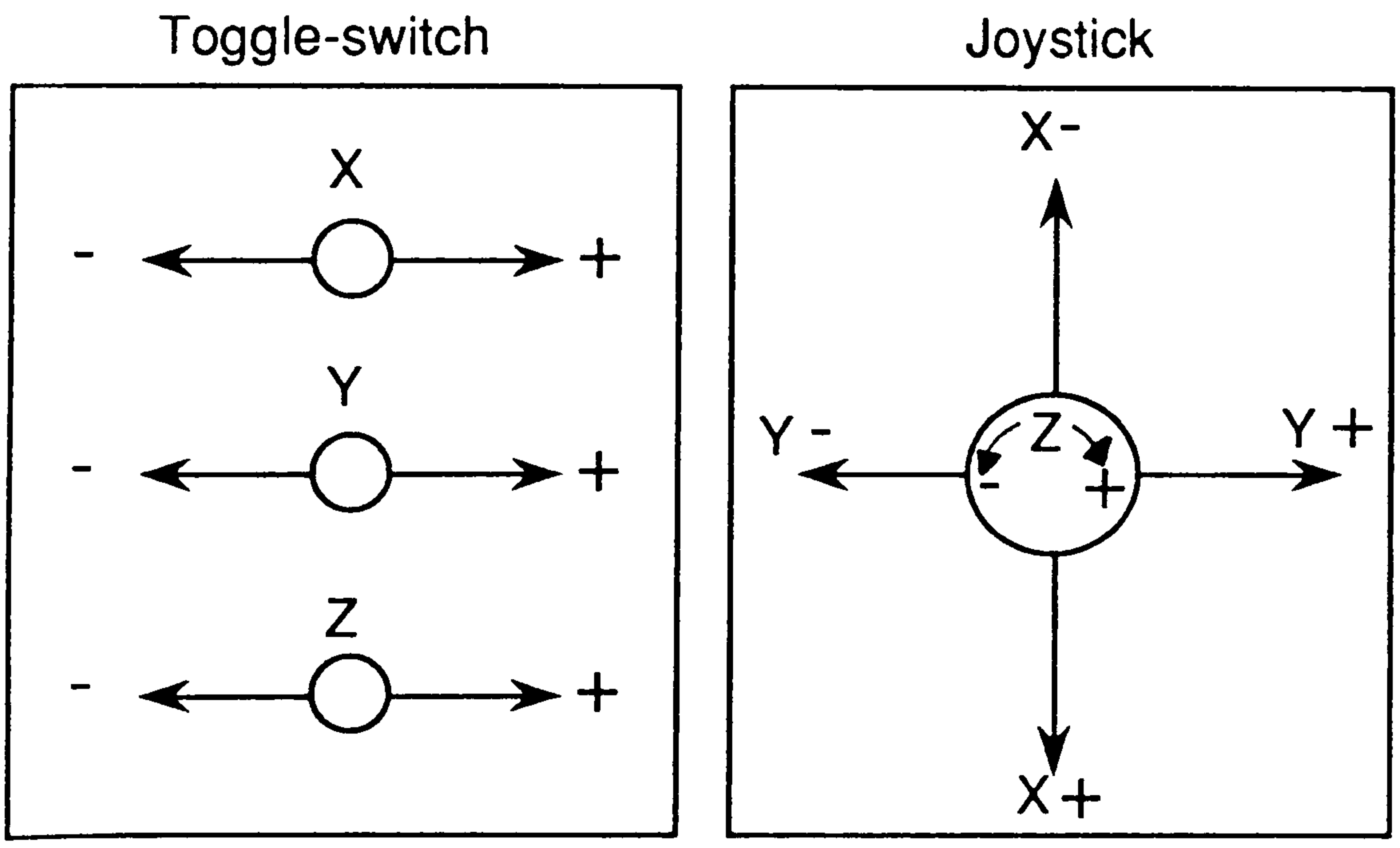
Figure 5.14 Control box faceplates used in experimental stage 2

a) Experiment 3: joint mode


Toggle-switch

Joystick

b) Experiment 4: world mode


Toggle-switch

Joystick

the ASEA control is in fact designed to be operated from the left side of the robot (Brantmark et al, 1982). The labelling on the joystick was therefore compatible with robot movement when viewed from the left orientation. As it happened, in experimental stage 2 the left orientation was used for subject 'training' and so control-robot movement compatibility was provided at the training position. The control-robot movement reversals produced by changes in human-robot orientation, described in section 4.4.3, still apply but are relative to the training position which, in this case, is not the front orientation.

The decision taken to label the joystick as well as the toggle switch control was to try to make conditions as similar as possible between the two controls and it was thought that if errors were made using the joystick due to physical control-motion incompatibility then these would occur regardless of labelling.

Experimental stage 3

The faceplates used in experiment 3 are shown in Figure 5.15. The toggle-switch was again labelled in accordance with the actual PUMA teach pendant. However, the joystick labelling had been altered so that it was compatible with robot movement when viewed from the front orientation in accordance with Creed's assumptions rather than in accordance with the actual ASEA design. The direction labelling (+/-) was made compatible with user expectations as identified in the previous experiments; control movements to the right, forward or clockwise were labelled '+', and movements to the left, backward or anticlockwise were labelled '-'. With this labelling method, control-robot movement compatibility was achieved when viewed from the front orientation.

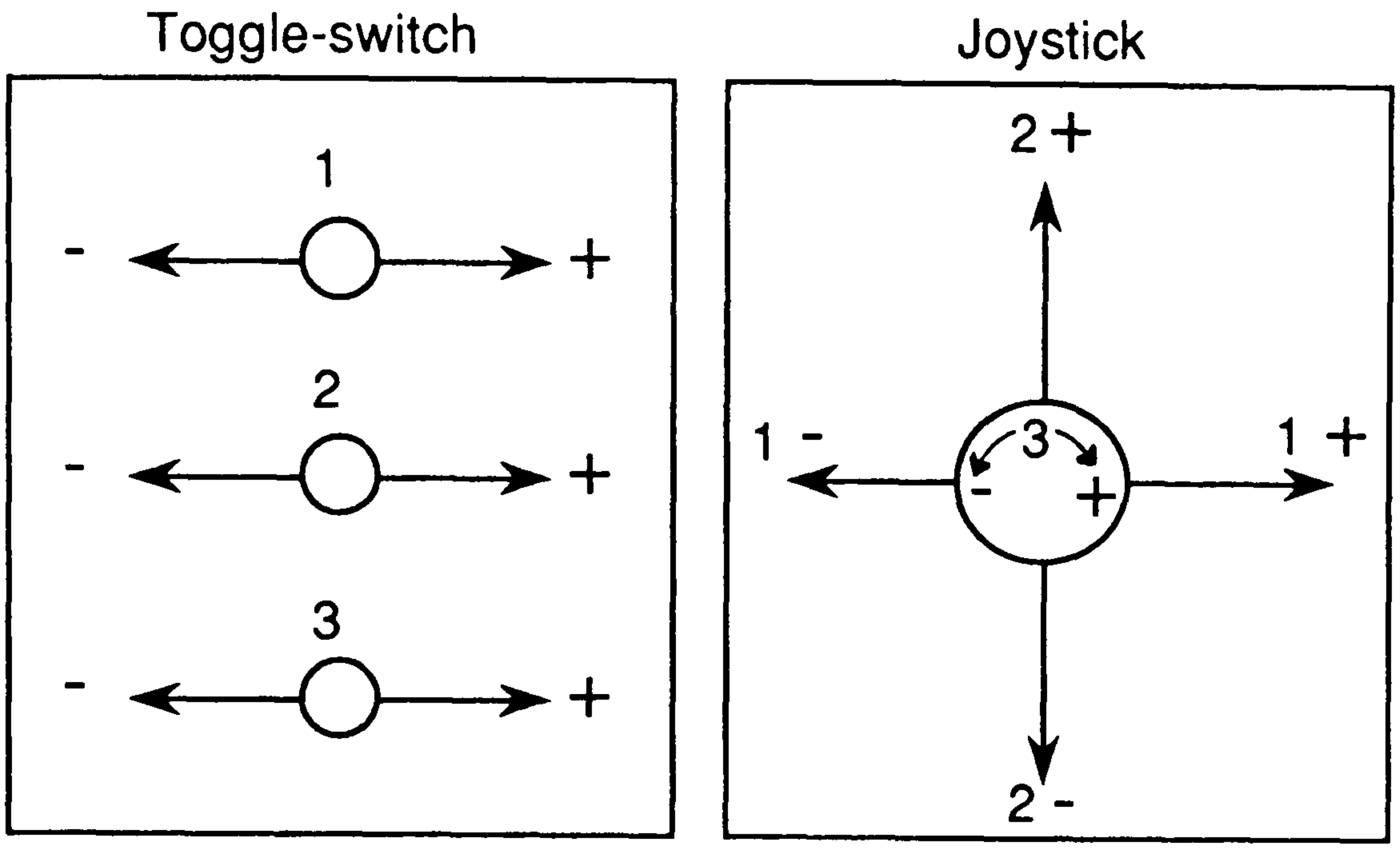
For data collection both teach boxes were connected to a BBC micro computer as described below.

5.3.5 Computer interface

The BBC micro computer was initially used to record the control selections made in experimental stage 2 and in stage 3 was additionally used to drive the PUMA robot. This was achieved in different ways for each of the teach boxes. Figure 5.16 shows the information

Figure 5.15 Control box faceplates used in experimental stage 3

a) Experiment 5: joint mode



b) Experiment 6: world mode

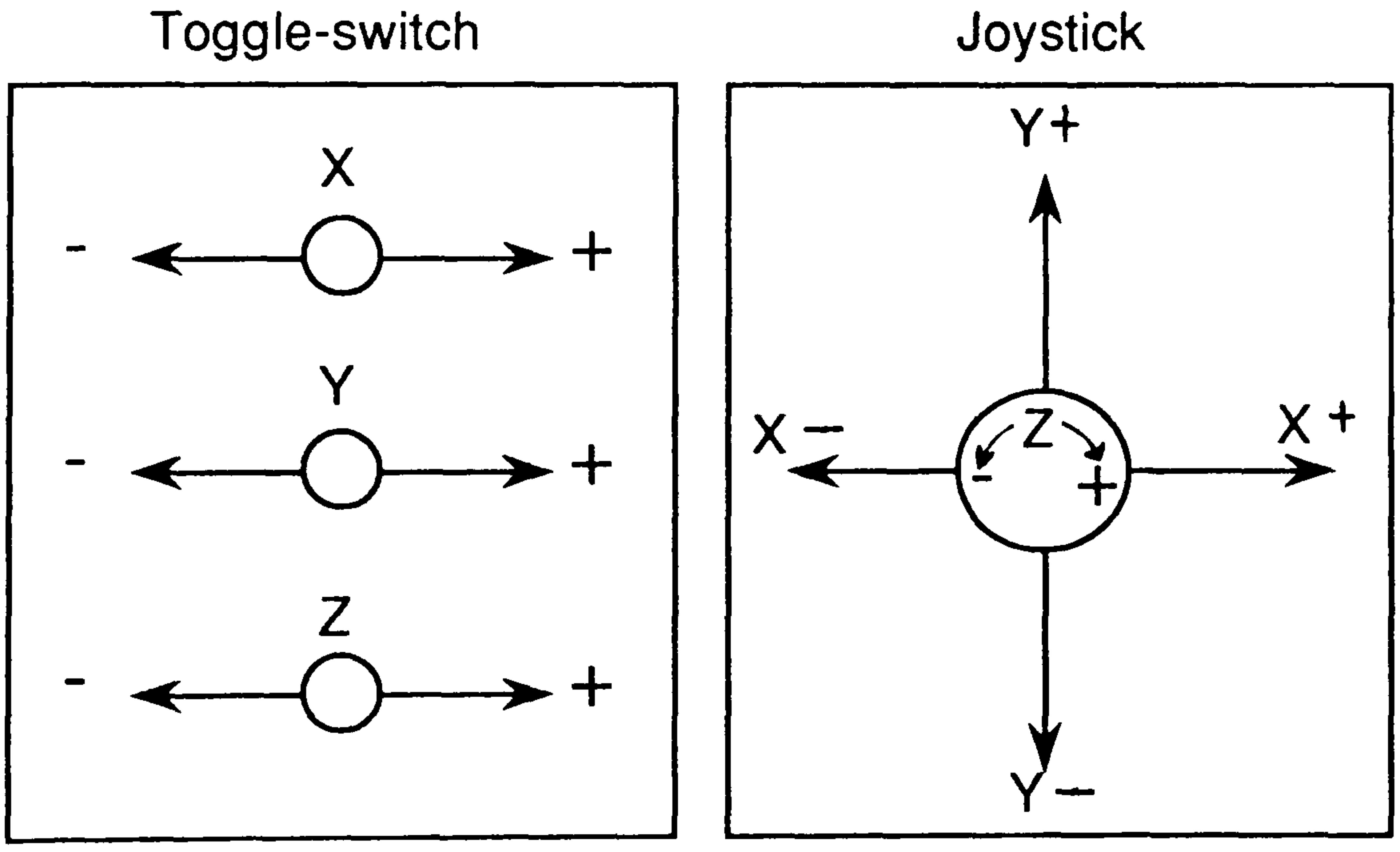
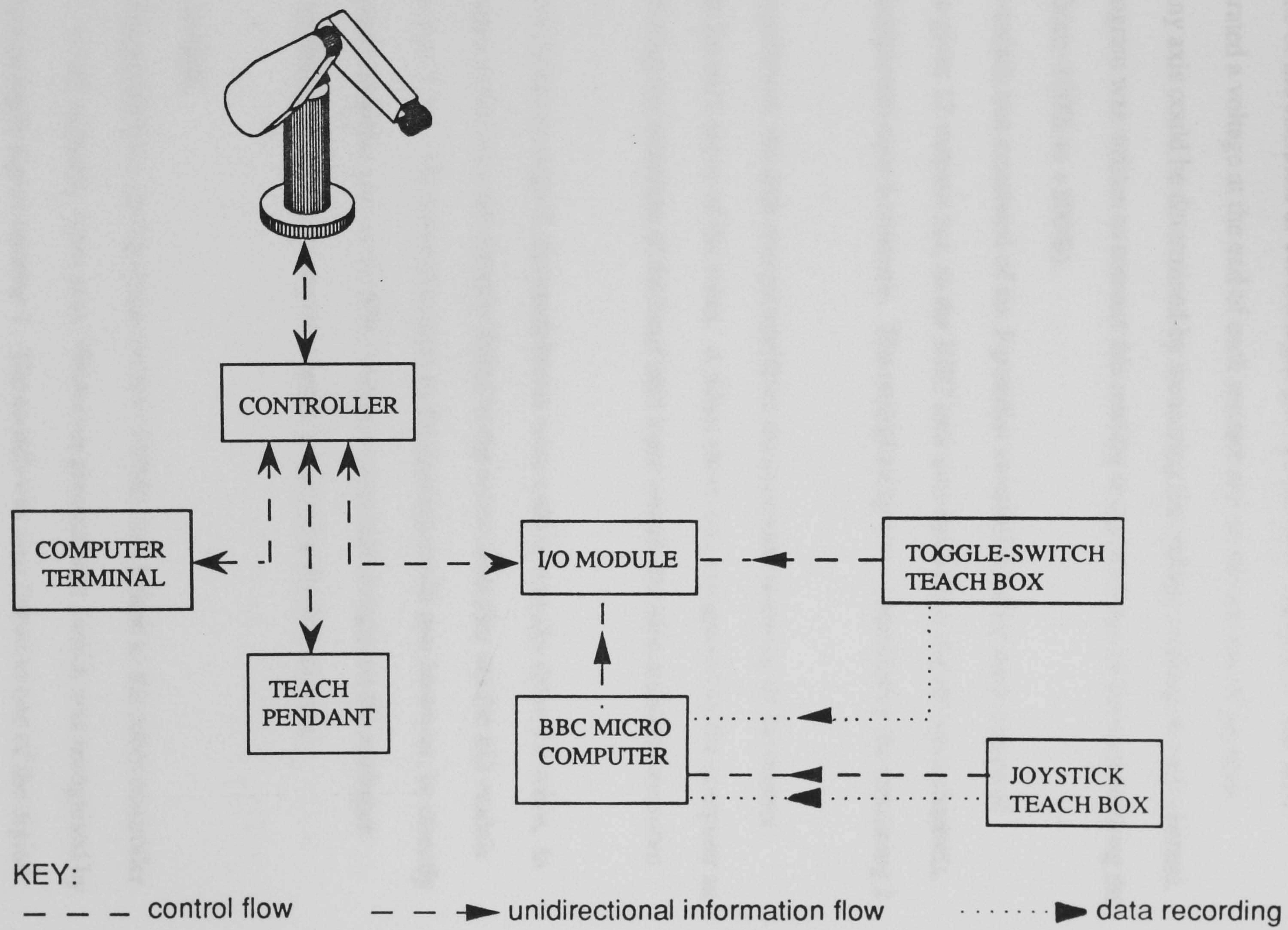


Figure 5.16 Information flow between the experimental teach boxes and the PUMA system



flow between the teach boxes and the robot system.

The joystick consists of three variable resistors (one for each axis) which were each connected to one of the channels of the analogue port on the BBC computer. The BBC computer generated a voltage at the end of each resistor and so the amount of joystick deflection on any axis could be determined by measuring the voltage reading on each channel. A computer program was written to convert this reading to a percentage of movement along the axis (ranging from -100% to +100%).

The toggle-switch box consisted of six 3-position switches (one for each degree of freedom). This gives 12 outputs but, as the BBC user port has only 8 digital input channels, the data was multiplexed onto 6 channels. The multiplexing was controlled by the remaining 2 channels.

After the experiment, the data was printed from the computer showing all the control selections made for each move of the robot. A robot move was recognised by the computer as everything following the initiation of the hand held input switch that also activated the robot program.

For the experiments in stage 3, the teach boxes were used to actually drive the robot. In this case, the toggle-switches were directly linked to the robot controller via the I/O module described in section 5.3.1. The potentiometers in the joystick could not, however, be directly linked to the robot controller and so the BBC computer was used to convert the analogue information from the joystick into the digital signals required by the I/O module.

5.3.6 Input switch

A double-pole pushbutton spring-return switch (PBSR) was linked to the robot controller input channel 1 via the normally open pole. Whenever pressed, this switch was recognised by the robot program as input signal number 1. The switch was also linked to one of the digital input channels of the BBC analogue port via the normally closed pole. This could then be recognised by BBC program as the initiation of robot moves or a request to start timing a subject's response.

5.3.7 Task equipment

For the experiments involving verbal description of robot positions (stage 1), a Sony cassette tape recorder was used with a microphone placed in front of the subject.

For the experiments in stage 3, subjects were given tasks that required them to move the robot in certain ways. For the WORLD mode task, a 3-dimensional maze of dimensions 280 x 280 x 110mm was constructed from cardboard and polystyrene blocks. Using these materials prevented any damage to the robot in case the robot was moved in the wrong direction. A path was marked on the top of the box to show the direction in which the robot should be moved (see Figure 5.17). A pencil was placed vertically in the robot gripper to act as a guide for the subjects; the pencil had to be moved along the marked path of the maze, which, due to its 3-D nature included changes in the X,Y and Z planes. A stopwatch was used to record task completion time.

For the JOINT mode experiment it was not possible to use the 3-D maze since the path of joint movements is different to those of world movements. Nor was it possible to devise an exactly equivalent task due to the complexity of joint movements. Consequently, a set of instructions consisting of individual joint movements in the form of a joint number and direction arrow were presented on acetate sheets (see Figure 5.18). These were then individually projected onto a screen in front of the subject. This was also synchronised with the pressing of the input switch to initiate timing of the subject's response. The manner in which the subject actually moved the robot was observed and recorded by the experimenter.

5.4 Experimental subjects

In all of the experiments, subjects consisted of volunteers from the Department of Production Engineering and Production Management at the University of Nottingham. In the early experiments these were unpaid volunteers but, as the later experiments became more time consuming, the subjects were paid for their participation (£2 for participation in experimental stage 2 and £8 in experimental stage 3). In some experimental stages, they were undergraduate students and in others they were postgraduate students and research staff depending on

Figure 5.17 3-dimensional maze used as a tracking task in experiment 6

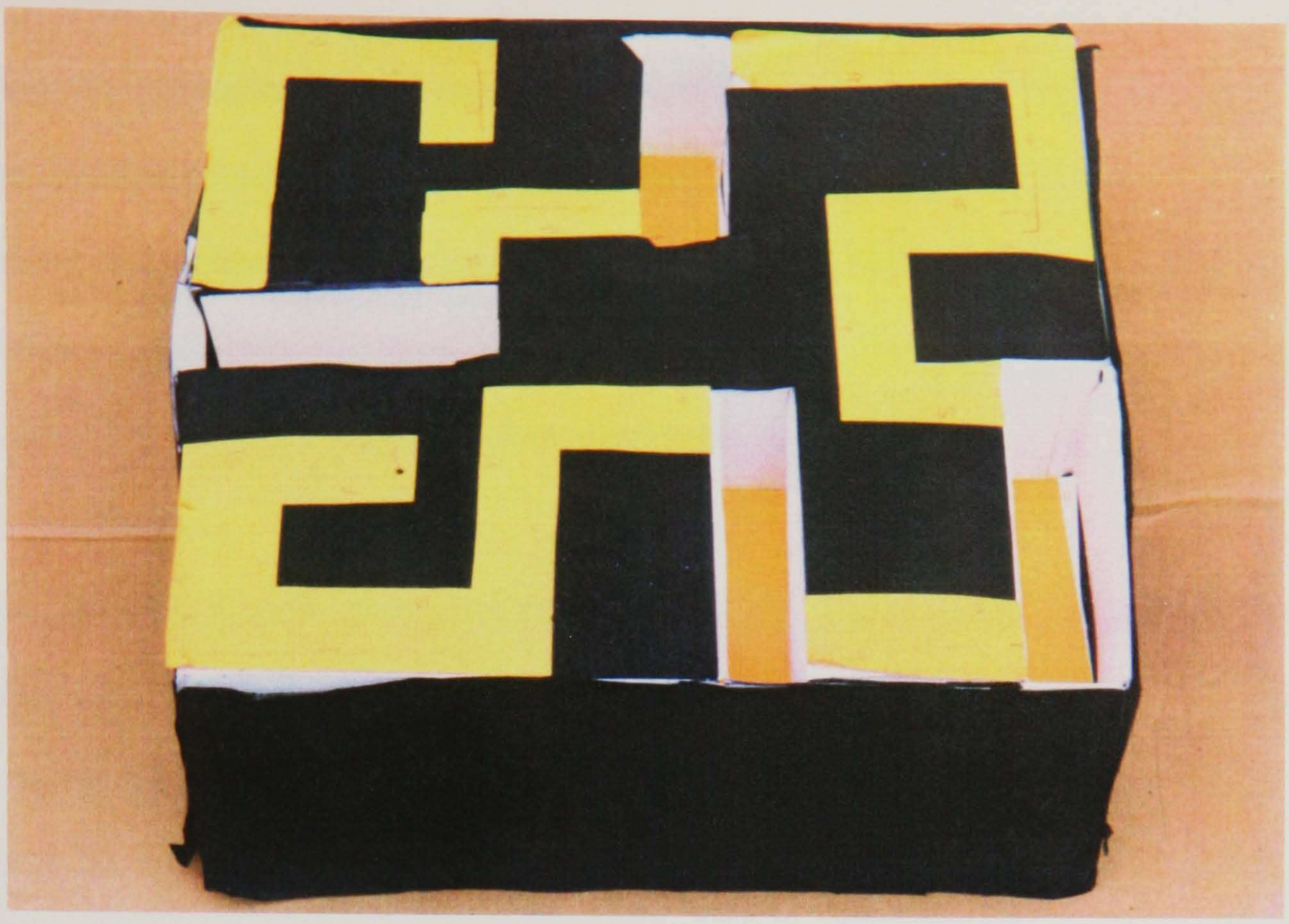
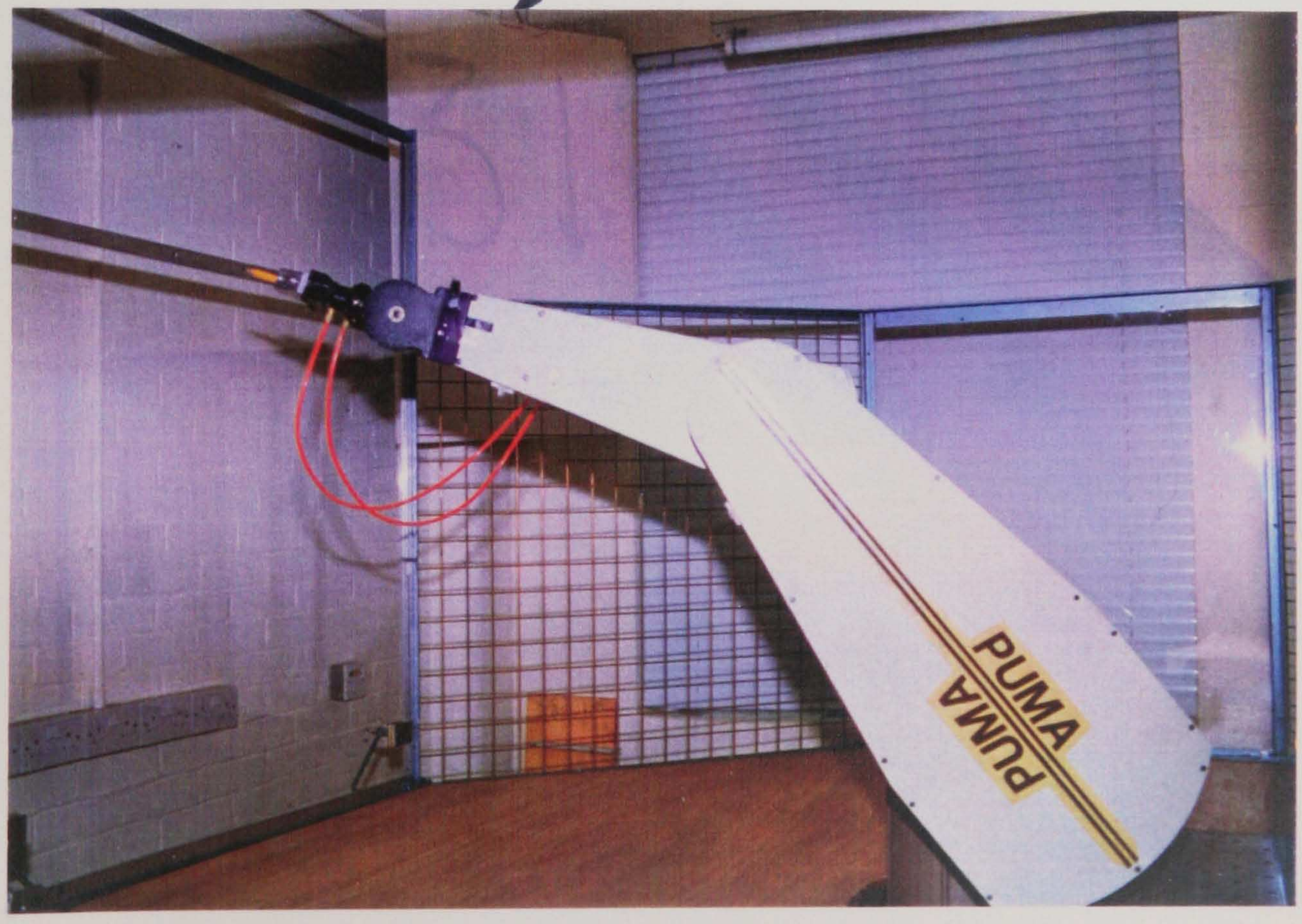


Figure 5.18 Example of a control movement instruction presented in experiment 5

screen showing joint movement required



availability. At no stage were they mixed. The age range of the subjects was 18 - 30 years.

Before participating in the experiments, the subjects gave details of their academic experience (qualifications) and any experience they had of industrial robotics. They were found to have similar academic backgrounds (mathematics and sciences) and, although some of them had seen industrial robots in operation (either on television or on factory visits), none had any experience or knowledge of robot programming.

As there were no 'expert' programmers available, the experiments were aimed at assessing the performances of 'naive' subjects. The use of naive subjects provided the advantage that the experiments would identify users ‘natural expectations’ of the control-robot movement relationships, as opposed to an ‘expert's’ knowledge and experience in these types of tasks. It is understood that naive subjects will be less able to accurately control robot movement, but their performance characteristics should provide greater indication of the types of control errors that may occur during robot programming.

To maintain subject naivity across all the experiments, a subject could only be used in one experiment as the effects of learning were difficult to assess. In total, 96 subjects were used in 6 experiments within the three stages, each experiment utilising 8 - 20 subjects depending upon subject availability and duration of the experimental task.

CHAPTER 6 - EXPERIMENTAL WORK

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6.1 Stage 1: Perception of robot movement

This stage of the experimental work investigated naive subjects' comprehension of robot movement. There were two experiments carried out. The first was an exploratory experiment to determine how subjects describe individual robot joint movements in different robot arm-configurations. The second experiment examined in more detail the different terminologies used in the first experiment to describe joint motion. This was in order to determine whether the terminologies would affect subjects' perception of joint movements differently when viewed in different arm-configurations.

6.1.1 Experiment 1: Description of robot movement

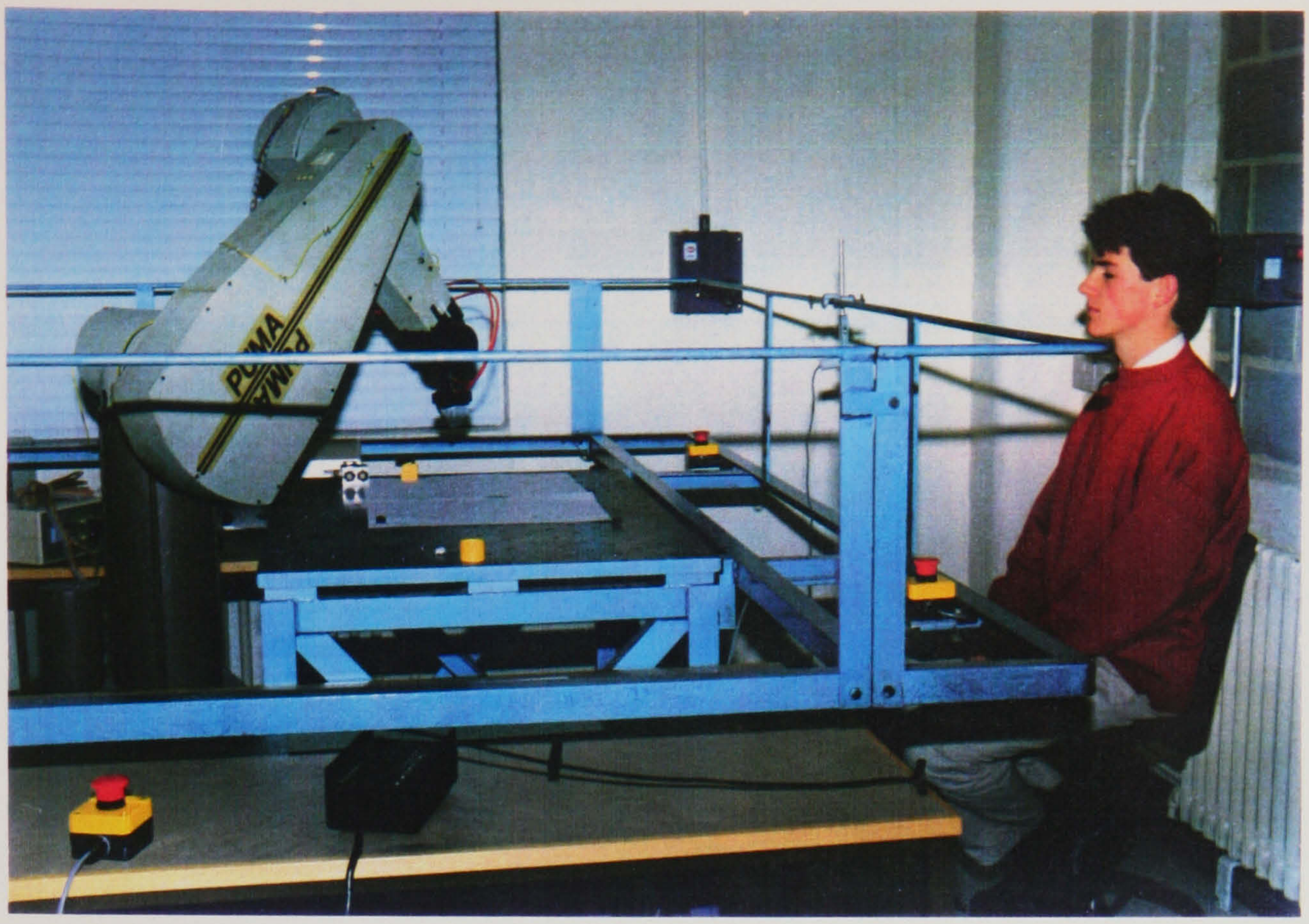
The analyses of robot teach pendants (discussed in section 2.2) have shown that there is a variety of control labelling for robot joint movement. The labelling of the joints themselves vary (e.g. waist, shoulder, elbow; 1,2,3; A, B, C) and the labelling for direction of movement can be expressed in words (up,down, in, out), legends (+, -) or graphics (↗, ↖). This lack of any standard terminology inspired the first experiment of the research programme. It was considered necessary to determine how untrained subjects would label the robot joints and movement directions because, the method which is most intuitive to observers, may cause less ambiguity for all operators in recognising which control is used for which joint movement.

6.1.1.1 Procedure

The subject was seated directly in front of the robot as shown in Figure 6.1, and remained in this position throughout the experiment. The robot was positioned at one of the four configurations (A, B, C, D) previously shown in Figure 5.9.

From each configuration the robot was moved through a sequence of 12 joint movements one joint at a time. The 12 joint movements represented a move of each of the six joints in each direction (+ve, -ve) once only. Each movement was initiated by the experimenter

Figure 6.1 Robot set up with subject seated at the front orientation



pressing the input switch to the robot controller. After each move the subject described the movement in terms of which part of the robot had moved and in which direction. When the subject indicated that they had finished, the experimenter initiated the next move. Thus, the subject was allowed unlimited time to give an answer. After each complete sequence of moves the robot moved to another configuration and the individual joint movement sequence was then repeated from the new configuration.

6.1.1.2 Design

8 subjects took part in the experiment; 7 male, 1 female. All were undergraduate students aged between 18 and 22 years. They all performed exactly the same task. The sequence of joint movements was the same in each configuration but the presentation order of configurations was randomised between subjects.

6.1.1.3 Results

For clarity, the results will be presented separately for joint description and description of movement direction.

1. Joint description

The responses given by each subject to identify each of the six robot joints are shown in Table 6.1. It can be seen that all the subjects used words to describe the joints; Joint 1 was mainly described as body or base. Joint 2 was mainly described as shoulder whilst Joint 3 was mainly described as forearm or arm. Furthermore, most subjects used a different term for the last 3 joints (e.g jaw, wrist, gripper, finger, end, tool, manipulator), but only two subjects clearly distinguished between these last 3 joints; subject 2 described them as; large wrist, wrist and small wrist; subject 4 described them as; upper forearm, wrist and finger. All the other subjects displayed an inability to identify these three joints differently.

Table 6.1 Subjects' descriptions of each robot joint

Subject	Robot Joint					
	1	2	3	4	5	6
1	base	body	arm	jaw	jaw	jaw
2	body	shoulder	elbow	large wrist	wrist	small wrist
3	robot	robot	arm	manipulator	gripper	gripper
4	stem	shoulder	forearm	upper forearm	wrist	finger
5	body	robot	top half	end	end	end
6	base	lower arm	upper arm	tool	tool	tool
7	vertical axis	shoulder	forearm	wrist	jaw	jaw
8	body	whole arm	second arm	manipulator	manipulator	manipulator

2. Description of movement direction

The responses given by the subjects to describe each joint movement in each configuration are shown in Table 6.2. In general, the subjects tended to use one of two types of description for robot movement; either as a clockwise/anti-clockwise rotation of the joint, or a left/right or up/down movement. Some subjects changed the type of description they used depending upon which joint had moved. Thus, in the majority, clockwise/anti-clockwise was used to describe the movement of joints 1,4 and 6 (80% of the total responses for these joints), whereas up/down was used to describe the movement of joints 2,3 and 5 (72% of the total responses for these joints).

Furthermore, the robot arm configuration seems to have affected the responses particularly when up/down was used to describe joint movement. For example, the 2+, 3+ and 5+ movements were mostly described as 'up' in arm-configurations A and B (RIGHTY-arm) (69% of the total responses for these joint movements), but the same number of responses were given as 'down' when the joint movement was observed in configurations C and D (LEFTY-arm).

This experiment was intended only to indicate what terminologies for describing joints and joint motion would be used by naive subjects. As this was an exploratory experiment, with no hypotheses under examination, it was not appropriate to perform any statistical analysis on these data.

6.1.1.4 Discussion

This experiment has indicated that naive subjects will intuitively assign ‘human-like’ terms to describe individual robot joints (e.g. body, shoulder and arm). However, they have difficulty in clearly distinguishing between the three wrist joints.

Two main terminologies emerged for describing the direction of joint movement; either as a rotation (clockwise or anti-clockwise) or as a linear movement (left, right, up or down). In addition, the description of the direction of joint movement sometimes varied when the move was observed in different configurations.

Table 6.2 Subjects' descriptions of each joint movement in each robot arm-configuration

joint movement	robot arm-configuration			
	A	B	C	D
1+	ac (5) right (1) left (1) away (1)	ac (7) right (1)	ac (6) right (1) towards (1)	cw (6) right (2)
1-	cw (6) left (1) towards (1)	cw (7) left (1)	cw (6) left (2)	cw (7) left (1)
2+	up (6) ac (2)	up (5) down (1) ac (1) cw (1)	down (5) ac (3)	down (5) ac (2) cw (1)
2-	down (6) cw (2)	down (5) up (1) cw (1) ac (1)	up (5) cw (3)	up (6) cw (2)
3+	up (6) ac (2)	up (5) down (1) cw (2)	down (5) ac (3)	down (6) cw (2)
3-	down (6) cw (2)	down (5) up (1) cw (1) ac (1)	up (6) ac (2)	up (5) cw (3)
4+	ac (3) cw (1) down (1) up (1) right (1)	ac (8)	ac (7) down (1)	ac (5) cw (1) right (2)
4-	cw (3) ac (2) left (2) away (1)	cw (7) ac (1)	cw (8)	cw (6) right (2)
5+	up (6) ac (2)	up (5) down (1) cw (2)	down (6) ac (2)	down (6) ac (2)
5-	down (6) cw (2)	down (4) up (1) ac (3)	up (6) cw (2)	up (6) ac (2)
6+	ac (5) right (3)	ac (8)	ac (7) cw (1)	ac (5) left (2) away (1)
6-	cw (4) ac (1) left (2) away (1)	cw (7) ac (1)	ac (6) cw (1) right (1)	ac (5) cw (1) right (2)

Key:- cw = clockwise, ac = anticlockwise

N.B. Towards and away should also read "from me"

The number of subjects who gave each response is given in brackets.

The robot arm-configurations A, B, C, D were shown previously in Figure 5.9

From this experiment the following hypotheses were established;

i) Terminology may influence ability to correctly identify individual joints.

ii) The terminology used to describe direction of joint motion (rotation or linear) may influence the consistency of how a given movement is described when viewed in different robot arm-configurations.

6.1.2 Experiment 2: Perception of joint movement in different arm-configurations

On the basis of the previous experimental findings, it was decided that a more detailed evaluation of robot movement perception needed to be carried out (Gray and Wilson, 1989).

In this experiment subjects were shown how the robot moved in joint mode and were told how they should describe each movement. The subjects were thus provided with a terminology to describe the movements they saw and their responses were compared for consistency with actual movement. Two joint description terminologies were compared: words (waist, shoulder, elbow, pitch, yaw, roll), or numbers (1,2,3,4,5,6). These terminologies were selected because the previous experiment had shown that subjects intuitively use words to describe robot joints. However, as no single set of words had emerged from experiment 1, those selected were taken from the PUMA manual to describe each of the robot joints. The numbers terminology was selected as the labelling on the Unimate teach pendant uses numbers for each joint. Two motion direction terminologies were compared; joint rotation (clockwise/anti-clockwise), or linear movement (left/right or up/down).

The previous experiment had identified inconsistencies in direction of movement descriptions for subjects using a linear movement terminology when the robot was viewed in different configurations. Because these inconsistencies were not so evident when a rotation terminology was used, it was considered that different strategies for motion referencing may be present in each case. It was thought that subjects using the joint rotation terms would use the centre of the robot for motion reference and that their frame of reference would consequently change with different robot configurations, producing a consistent description of joint movement regardless of robot arm-configuration. On the other hand it was thought that, in the group using the linear movement terms, their view of robot motion would be in relation to themselves, producing inconsistent descriptions of joint movements as a result of changes in robot arm-configuration (as previously described in section 4.4.2.2).

6.1.2.1 Procedure

The subject was seated directly in front of the robot, with the robot in configuration A , as shown in Figure 5.9. This configuration has the robot arm in a 'normal' position and was thus used as the "training condition". Each of the 6 joints were moved in both directions and each movement was described by the experimenter in accordance with the particular treatment group for the subject. In order to help counter learning and memory effects, half of the subjects were shown the joints in ascending order (1,2,3,4,5,6), and half of them were shown the wrist joints first (4,5,6,1,2,3). When the experimenter was satisfied that the subject had understood the descriptions, the experimental task began.

Starting from one of the four configurations (A, B, C, D), the robot arm moved one joint at a time through a sequence of moves. After each move, the subject stated which joint of the robot had moved, and in which direction. The answers were recorded on the cassette tape recorder. After each answer, the experimenter initiated the next joint movement using the input switch. The subject was thus allowed unlimited time to give an answer. The task sequence consisted of one move in each direction for each of the six robot joints, and the sequence of moves was the same in all four robot configurations but the order of presentation of each configuration was randomised.

6.1.2.2 Design

Twenty undergraduate students aged 18 - 22, 16 males and 4 females, participated as volunteer subjects. The experiment consisted of four treatment groups, being combinations of joint description and motion direction terminologies; words/ joint rotation, words/ linear movement, numbers/ joint rotation, numbers/ linear movement. The subjects were randomly assigned to one of these 4 groups. In the analysis, each terminology was taken separately and data collapsed across groups as appropriate.

Analysis 1. Joint identification

For evaluation of joint identification errors a two factor (2 x 6) mixed design was applied. The factors were defined by;

a) descriptive terminology (words or numbers)

b) robot joint (1,2,3,4,5,6).

Subjects' performance was evaluated by correct identification of the joint that moved.

The null hypotheses under examination were;

Ho1: There will be no difference in joint identification errors using words terminology and joint identification errors using numbers terminology.

Ho2: Joint identification errors will be equal on all robot joints.

Ho3: There will be no interaction on joint identification errors between terminology group and robot joints.

Analysis 2. Direction of motion

For evaluation of motion control errors a two factor (2 x 4) mixed design was applied. The factors were defined by;

a) motion direction terminology (joint rotation or linear movement)

b) robot configuration (A,B,C,D).

Subjects' performance was evaluated by consistency of movement descriptions with those used in the training condition. For the purpose of analysis, an inconsistent description of any move (e.g. 3+ described as 'up' in the training condition but 'down' in another condition), even though it may be correct in terms of what is actually observed in a world frame of reference (i.e. the joint did move down), was classed as an 'error' in terms of not recognising the move to be the same.

The null hypotheses under examination were;

Ho4: There will be no difference between direction errors using joint rotation terminology and direction errors using linear movement terminology.

Ho5: Direction errors will be equal at each robot arm-configuration.

Ho6: There will be no interaction on direction errors between terminology group and robot arm-configuration.

6.1.2.3 Results

Analysis 1. Joint identification

The mean error scores of joint identification are shown in Table 6.3a. In general, for both the words and numbers terminology groups, the error scores were very low, particularly on the first three joints. Looking at the raw data, as given in Appendix IV.1i, it can be seen that many of the subjects in both groups made no errors at all. With this type of data it is difficult to perform a satisfactory analysis of variance and so a transformation of the data (natural logarithm (x+1)) was performed on the data. The log mean error scores are shown in Table 6.3b.

The Analysis of Variance table for the transformed data is given in Appendix IV.1ii. Although there were more overall errors for subjects using words to describe the joints, this was not significantly different; F(1,18) = 0.43, p=0.52. There was a significant difference in errors made on different joints; F(5,90) = 7.44, p=0.000. A Tukey test for comparison of means was carried out (see Appendix IV.1iii), which identified significant differences between the following log means; joints 1 and 2 with joints 4 and 6 (p=0.05); joint 3 with joint 5 (p=0.05); and joints 1 and 2 with joint 5 (p=0.01).

The interaction between the descriptive terminology used and errors on different joints, although not significant, is worth reporting; F(5,90) = 2.23, p=0.057. The interaction is shown in Figure 6.2. Assessment of the simple main effects indicated that the effect of joint at each terminology group was significant; words group (F(5,90) = 7.12, p=0.000), numbers group (F(5,90) = 2.56, p=0.32). No significant effects of group were observed at any of the joints (see Appendix IV.1iv). A Tukey test for comparison of means within each terminology

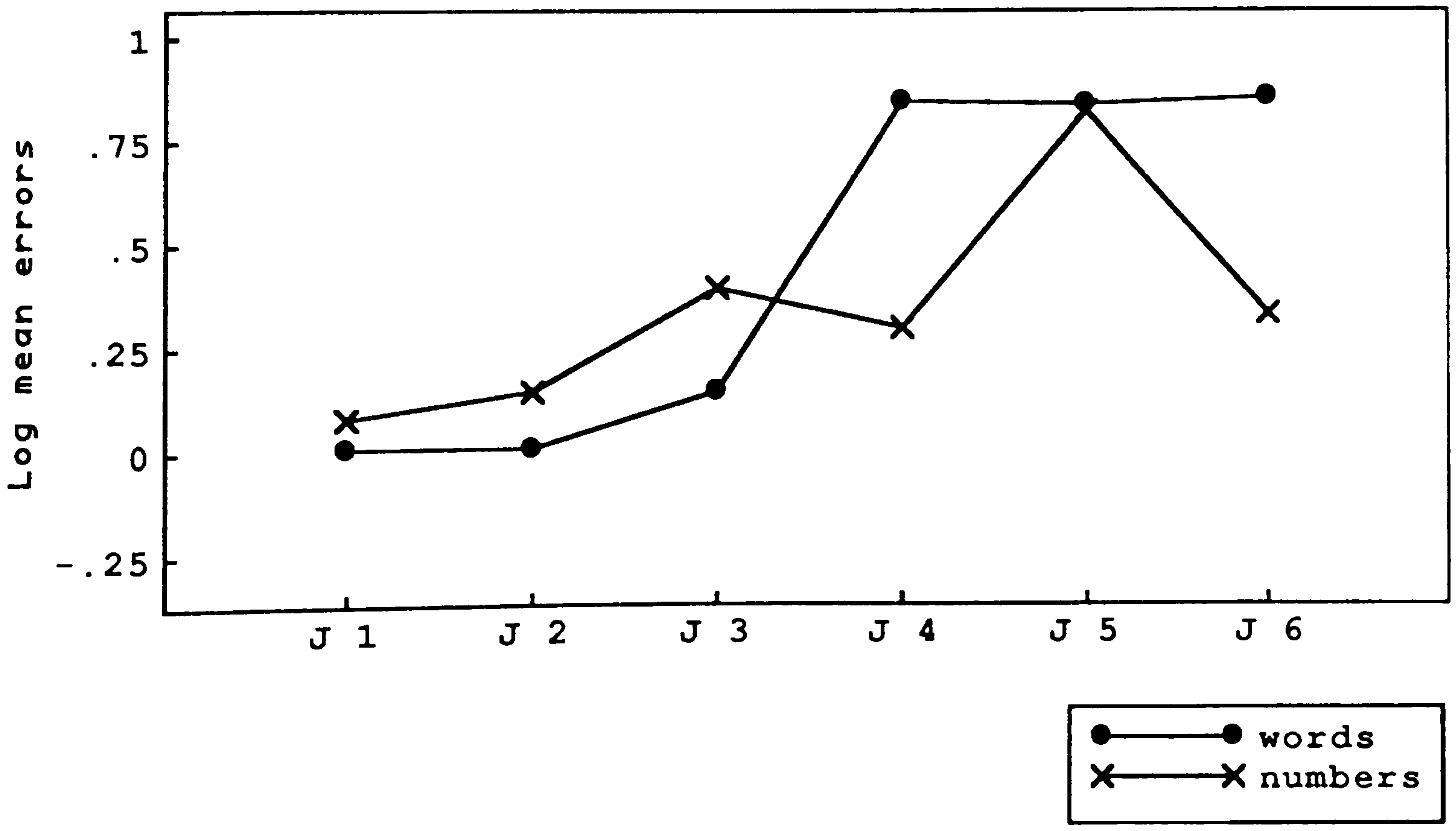
Table 6.3a Mean joint identification errors for each terminology group

Terminology group	Robot joint						Overall mean
	1	2	3	4	5	6	
Words	0.0	0.0	0.2	2.3	2.2	2.6	1.2
Numbers	0.1	0.2	1.0	0.5	1.8	0.5	0.7
Overall mean	0.05	0.1	0.6	1.4	2.0	1.6	

Table 6.3b Log mean joint identification errors for each terminology group (transformed data)

Terminology group	Robot joint						Overall log mean
	1	2	3	4	5	6	
Words	0.00	0.00	0.14	0.84	0.83	0.84	0.44
Numbers	0.07	0.14	0.39	0.29	0.81	0.32	0.34
Overall log mean	0.03	0.07	0.26	0.56	0.82	0.58	

Figure 6.2 Log mean errors in joint identification using either words or numbers to describe the joints (transformed data)



group was carried out (as shown Appendix IV.1v). Within the words group the log mean errors on joints 1, 2 and 3 were significantly different from those on joints 4, 5 and 6 (p=0.05). Within the numbers group the only significant differences obtained were between joints 1 and 2 with joint 5 (p=0.05).

Analysis 2. Direction of movement

The raw data for direction of movement errors are given in Appendix IV.2i. Although there were a few cases where no errors had been made, it was decided that transformation of the data was not necessary. The mean error scores of movement descriptions are shown in Table 6.4. The Analysis of Variance table is given in Appendix IV.2ii. There was a significant difference in errors between the terminology used, F(1,18) = 21.51, p=0.0002; more errors were made using the linear movement terminology, an average 51% error rate compared to 29% for the rotation terminology group. There was also a significant difference in errors made between the configurations; F(3,54) = 26.31, p=0.0000; with configuration A (the training condition) producing least overall errors.

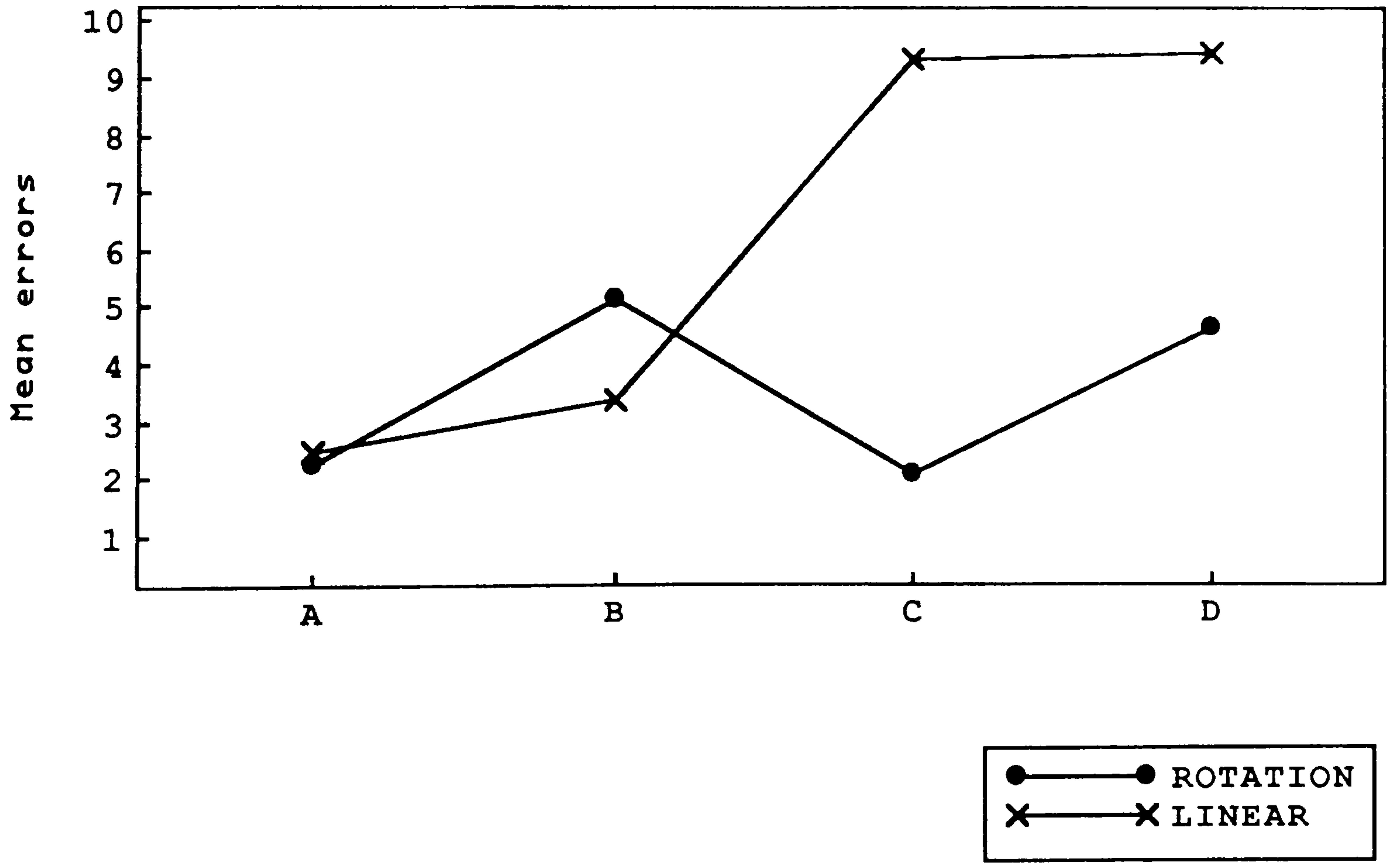
The interaction between the two factors was significant; F(3,54) = 28.12, p=0.0000. This is shown in Figure 6.3. Assessment of the simple main effects, as shown in Appendix IV.2iii, identified significant effects of terminology group at configurations C (F(1,18) = 149.41, p=0.000) and D (F(1,18) = 30.14, p=0.000). No significant effects were observed at configurations A (F(1,18) = 0.045, p= 0.834) and B (F(1,18) = 2.88, p=0.107). The effect of configuration at both groups were found to be significant; rotation terminology group (F(3,54) = 8.33, p=0.000), linear movement group (F(3,54) = 16.09, p=0.000).

A Tukey test of comparison between means within each terminology group was carried out; T(4,72) = 2.3, p=0.05, as shown in Appendix IV.2iv. In the rotation terminology group the means for configurations B (5.1) and D (4.6) were found to be significantly different from those at configurations A (2.2) and C (2.0). Whereas, in the linear movement terminology group the means for configurations C (9.3) and D (9.4) were significantly different from those at configurations A (2.4) and B (3.3).

Table 6.4 Mean errors in direction-of-movement descriptions for each terminology group at each robot arm-configuration

Terminology group	Robot arm-configuration				Overall mean	% error rate
	A	B	C	D		
Rotation	2.2	5.1	2.0	4.6	3.5	29.1
Linear movement	2.4	3.3	9.3	9.4	6.1	50.8
Overall mean	2.3	4.2	5.6	7.0		
% error rate	19	35	46	58		

Figure 6.3 Mean errors in direction-of-movement descriptions made by each terminology group at each robot arm-configuration



The differences between the robot configurations are as follows;

A and B, C and D = reversal by rotation.

A and C, B and D = 'over-the-top' flip reversal.

A and D, B and C = rotation + 'over-the-top' flip reversal.

The difference in errors caused by these changes in position are shown in Table 6.5. The combined increase in errors for each type of configuration change are shown in Table 6.6. It can be seen that, in the rotation terminology group, more errors were caused as a result of robot rotation, whereas in the linear movement group more errors were caused as a result of 'over- the-top' or 'arm-flip' reversal.

6.1.2.4 Discussion

In this experiment it was found that terminology for joint identification did influence ability to correctly identify individual robot joints. The differences observed in the comparison of means test within each terminology group to some extent demonstrated the difficulty that subjects had shown in experiment 1 in describing the three wrist joints. In the "words" group, virtually no errors were made identifying the waist, shoulder and elbow joints but significantly higher errors were made on all three wrist joints. In the "numbers" group, few errors were made on all joints except for joint 5. However, the non-significant interaction observed in the analysis of variance, together with the non-significant effects of terminology group on joints observed in the simple main effects assessment, implies that there really were no differences between the groups in their performances. Furthermore, the raw data for these error scores (given in Appendix IV.1) shows that the most of the errors were made by a few of the subjects (5/10 in the words group and 2/10 in the numbers group). This produced "noisy" data and therefore it should be concluded that terminology did not have a strong influence on joint identification ability.

For direction of motion, terminology did influence consistency of movement description when viewed in different arm-configurations. As was expected, this effect was greater for the group using a linear movement terminology than those using a rotation terminology; each

Table 6.5 Increase in error scores for each terminology group as a result of changes in robot position

position change	Terminology group	
	rotation	linear
A - B	26	1
C - D	29	9
A - C	2	69
B - D	5	61
A - D	24	60
B - C	31	70

Table 6.6 Increase in error scores for each terminology group as a result of changes in robot arm-configuration

arm-configuration change	Terminology group	
	rotation	linear
rotation	55	10
arm flip	7	130
rotation + arm flip	55	130

group gave 50% and 29% inconsistent responses respectively. It should be noted, that the maximum score of inconsistent responses that would be expected is 50% since in only two of the four configuration conditions reversals in the 'appearance' of robot movements occurred. This result, therefore, supported the assumption that the "linear movement" group would describe robot movement in relation to themselves. However, the fact that any inconsistent responses had been made by the "rotation" group, indicates that, at least some of the time, these subjects also used this strategy.

From the results given in Table 6.6, it seems that the cause of inconsistencies in movement description is different for each terminology group. For the "linear movement" group inconsistent responses were observed when the robot had performed an 'arm-flip' reversal, whereas when the robot configuration rotated, the "rotation" group gave inconsistent responses. These effects may be illustrated with reference to Figure 4.11 (previously described in section 4.4.2.2). A movement of joint 2 in the positive direction would appear to the "linear movement" group to move 'up' when the robot was in a RIGHTY arm-configuration (Figure 4.11a), but 'down' when the robot was in a LEFTY arm-configuration (Figure 4.11b). If the same movement was described using a rotation terminology, it would appear to move 'anti-clockwise' when the robot was in the normal configuration (Figure 4.11a), but 'clockwise' when the robot was rotated (Figure 4.11c).

Consequently, these results suggest that the linear movement terminology is more likely to produce inconsistent movement descriptions. At this stage of the research, no further explanation can be provided but, in the light of later findings, these results are reconsidered in section 6.2.3.

6.2 Stage 2: Perception of control-motion compatibility

This experimental stage investigated teach pendant usability under different conditions of human-robot orientation. Two teach pendant designs were compared; the Unimate toggle-switch pendant and the ASEA joystick pendant (described in section 3.4). Due to technical difficulties involved in interfacing the actual teach pendants to the experimental equipment, mock-up control boxes were made (as described in section 5.3.4). Unfortunately, these could not be used to actually drive the robot, because the software necessary for interfacing was not yet fully developed. This prevented a direct evaluation of control selection performance, and therefore a method of assessing intended control selection was used. The robot was programmed to move through a task sequence and the experimental subjects were asked to identify the appropriate control on the teach pendant for each robot movement. While it may seem that this method of assessment is perhaps unrealistic, it has the advantage that the subjects receive no direct feedback of their control input and therefore would not be able to learn by "trial and error". Thus, it was expected that they would select the control which they intuitively associated with each movement, from which an assessment of control-display compatibility could be made.

There were two experiments carried out in this stage, examining these effects in Joint and World programming modes. The procedure and design for each experiment were the same. In the previous experiments the sequence order of individual joint moves had remained constant throughout the experiment. This was done to simplify the experimental design, but it was now considered that sequence order might influence perception of certain joints. In these experiments only the three major axes of movement were examined (joints 1,2 and 3 in Joint mode; axes X, Y and Z in World mode) as these produce gross movements of the robot arm and therefore represent greater collision hazards. This enabled random sequencing of joint order to be included in the experimental design.

On the basis of the results for joint identification in experiment 2 (i.e. there was no particular benefit in using either words or numbers to identify the joints), it was decided to use numbers for joint identification in all the experiments from now on. The main benefit of this was that teach pendant labelling would be much easier. It was not considered necessary to examine how subjects identify the axes of movement in world mode as these correspond to standard terms (X, Y and Z) with which most people are familiar.

It was considered important to continue to record the subjects' descriptions of directional movement in these experiments as this may give an indication as to the reason for incorrect control selections. For example, if a given movement was 'misperceived' by a subject (i.e. an inconsistent description of the movement was given), and they selected an incorrect control for that movement, their description of the movement may provide useful information to help determine why the wrong control had been selected. Therefore the subjects were asked to describe each movement in addition to making a control selection. However, it was also considered that the subjects in experiment 2 may have been restricted by the instruction to use a given terminology (i.e. rotation or linear movement) which may not represent the way that they would naturally describe robot motion. Thus, the subjects were allowed to choose their own terminology for describing direction of motion.

The experiments therefore considered three factors;

A. Evaluation of control selection performance.

B. Description of movement.

C. Assessment of any stereotype relationship between these two factors.

In addition to the experimental performance assessment, subjective measures were also taken;

D. Subject preferences for teach pendant design.

On the factors where statistical analyses were made, the null hypotheses under examination were as follows;

A. Evaluation of control selection performance.

Ho1: There will be no difference in control selection performance using either teach box.

Ho2: Human-robot orientation will not affect control selection performance.

Ho3: There will be no interaction between human-robot orientation and teach box used on control selection performance.

C. Assessment of stereotype associations.

Ho4: There will be no association between control selection and description of movement.

6.2.1 Procedure

It should be noted that the experimental set-up had now changed compared to stage 1. The robot had been moved to the centre of the experimental laboratory in order to allow access to all sides. Due to the small size of the laboratory, this limited the space available to the front, right and back orientations. Consequently, the training session took place at the left side of the robot rather than the front as in stage 1(previously shown in Figure 6.1). It was emphasised to the subject that they were positioned at the left side of the robot but, unfortunately, it would appear from the results that this aspect may have had a confounding effect on subject performance. This will be discussed later, when the experimental results are presented.

The training session consisted of the experimenter showing the subject the relevant degrees of freedom of robot movement for the experiment. For example, while moving joint 1, the experimenter would say; "This is joint 1, it can move this way [+ve] or this way [-ve]. No instructions for direction of motion labelling were given. The subjects were instructed that during the experiment they would see a sequence of these robot movements at each of four positions to the robot (front, right, left and back). A sequence consisted of six separate moves; one move of each degree of freedom in each direction (+ve, -ve). A different sequence order was presented from each position. During each move the subject was required to select and activate the appropriate control on the teach box that they thought would have produced that motion. These control selections were recorded on the BBC computer and later compared with the correct controls needed to produce each move. After each individual move, the robot was stopped and the subject was asked to describe in their own words what movement had occurred in terms of;

a) the joint that had moved, and

b) the direction it moved in.

The procedure for the World mode experiment was exactly the same as for Joint mode except that the subjects were instructed to describe movement of the TCP (or rather, a pencil placed in the robot gripper) along three axes; X, Y and Z. Also, the start position of the robot was not at the 'READY' position as in Joint mode since World coordinate movement from this position is not possible (i.e. the arm cannot move anywhere) because, in this position, the TCP is outside the world coordinate movement range.

6.2.2 Design

Twenty four research students, aged 25 - 30 years, took part in this experimental stage and were paid £2 for their participation. Twelve subjects, 8 males and 4 females took part in the joint mode experiment. In the world mode experiment there were 9 males and 3 females. The experimental task was repeated at each position using both teach boxes for all subjects. The presentation orders of teach control, orientation and movement sequence were counter balanced and randomly allocated to subjects.

A two factor (2 X 4) ANOVA with repeated measures design was used to assess the effect of the experimental factors on control selection errors made. The factors were defined by;

a) teach control (joystick and toggle)
b) subject-robot orientation (front, right, left and back).

Subject performance was evaluated by correct or incorrect control selection for each joint movement. However, an incorrect selection could be defined in two ways;

i) control error, where the wrong control number was selected, or
ii) direction error, where the correct control was moved in the wrong direction.

Thus, three separate analyses were carried out on the results;

Analysis 1. Total errors
Analysis 2. Direction errors
Analysis 3. Control errors.

6.2.3 Experiment 3: Perception of joint movement and control selection at different human-robot orientations.

6.2.3.1 Results

A. Control selection

The error scores for each teach control are shown in Table 6.7. It can be seen that most of the errors made, irrespective of type of teach control, were 'direction errors' (157/184 using the joystick and 171/175 using the toggle pendant). These are errors caused by the correct joint control being selected but moved in the wrong direction. The other type of errors are 'control errors' whereby the wrong joint control was selected. Because so few errors of this type were made (27 using the joystick and 4 using the toggle), the analysis was carried out on total error scores only.

The raw data for total error scores are given in Appendix IV.3i. The Analysis of Variance table is given in Appendix IV.3ii. There were no significant differences in overall error scores made between either teach control design; F(1,11) = 3.55, p=0.08. However it is important to note that a high error rate was obtained (approximately 60% for both teach boxes). In addition, there were no significant overall differences as a result of the subject's viewing position; F(3,33) = 1.69, p=0.19, nor was there any significant interaction between the teach control used and subjects' viewing orientation; F(3,33) = 2.64, p=0.07. However, closer examination of individual subjects' performances did reveal some trends.

Figure 6.4 shows the proportion of responses for each subject that were; correct control selections, direction errors and control errors, using each teach control. The most notable observation from the diagram is that subject number 3 was almost entirely responsible for the control errors made using the joystick teach control. All of the remaining subjects made direction errors in varying amounts using both teach controls. At first glance it was considered that, although wide variations in performance patterns were apparent, subjects could be grouped according to their responses, and this is shown in Figure 6.5. It would seem that the groups are somewhat arbitrary and that some subjects could be grouped differently. However,

Table 6.7 Control selection errors at each human-robot orientation

a) Using Joystick pendant

	Human-robot orientation				
	FRONT	LEFT	RIGHT	BACK	TOTAL
Total no. of robot moves	72	72	72	72	288
Direction errors	48	35	41	33	157 (54.5%)
Control errors	7	6	7	7	27 (9.4%)
Total errors	55	41	48	40	184 (63.8%)

b) Using toggle switch pendant

	Human-robot orientation				
	FRONT	LEFT	RIGHT	BACK	TOTAL
Total no. of robot moves	72	72	72	72	288
Direction errors	45	40	46	40	171 (59.4%)
Control errors	3	0	0	1	4 (1.4%)
Total errors	48	40	46	41	175 (60.7%)


Figure 6.4 Individual subjects' performance patterns using each teach control, showing the proportion of their responses that were; correct control selections, direction errors, and control errors

Figure 6.5 Individual subjects' performance data after grouping

the basis for grouping was similarity in the individuals' performance using both teach controls. These performance groups were found to be directly related to the subjects' descriptions of joint motion which are discussed in the following section.

B. Description of movement

Examination of the individuals' descriptions of joint motion revealed that they had used different terminologies to describe direction of movement (i.e. rotation or linear movement). In some cases, as shown in Table 6.8, a different terminology was used for different joints (e.g. motion of joint 1 was described as rotation by 11 subjects but only 7 subjects used this terminology for joints 2 and 3). Furthermore, it seemed that they had chosen different reference points from which direction of movement was defined. For example, for describing joints 2 and 3, four of the subjects who had used the rotation terminology defined a "clockface" as if it were viewed from the front of the robot (subjects 1, 5, 11 and 12). In contrast, two further subjects defined a "clockface" as if it were viewed from behind the robot (subjects 4 and 6). Consequently, for these two groups of subjects, the same joint movement would be described differently.

An additional observation of the descriptions was that, irrespective of the terminology used, some of the subjects showed patterns of consistency when a given joint was viewed from different orientations whereas others did not. Table 6.9 shows the descriptions given by all subjects for a movement of joint 3 in the positive direction. Subjects 1, 5, 11, 12, 4 and 6 gave consistent descriptions using a rotation terminology (but note from above that subjects 4 and 6 described the movement differently) and subjects 8 and 10 gave consistent descriptions using a linear movement terminology. The remaining subjects gave inconsistent responses when they viewed the movement from different orientations. Subject 2 described the movement as anticlockwise from the front and right orientations but as clockwise from the left and back orientations. Subjects 3, 7 and 9 gave a different description of the movement from each orientation; these descriptions referred to how that movement 'appeared' at the time.

Table 6.8 Terminologies used for describing direction-of-movement for each joint and the subjects who used them

JOINT	TERMINOLOGY	No. Subjects	SUBJECTS
1	rotation	11	1,2,3,4,5,6,7,8,10,11,12
	linear	1	9
2 & 3	rotation	7	1,2,4,5,6,11,12
	linear	5	3,7,8,9,10

Table 6.9 Subjects' descriptions of a joint 3 movement in the positive direction when viewed from different human-robot orientations

Subject	Human-robot orientation			
	FRONT	LEFT	RIGHT	BACK
1	ac	ac	ac	ac
5	ac	ac	ac	ac
11	ac	ac	ac	ac
12	ac	ac	ac	ac
4	cw	cw	cw	cw
6	cw	cw	cw	cw
8	up	up	up	up
10	towards	towards	towards	towards
2	ac	cw	ac	cw
3	left	forward	back	right
7	left	towards	away	right
9	away	towards	cw	away

These observations suggest that, independant of terminology used, the subjects differed in their frame of reference for motion direction, which was either fixed in relation to the robot or fixed in relation to the observer. This introduces the possibility of a different classification of subjects in terms of the frame of reference they used to perceive robot motion. These may be termed;

i)"robot-based" (i.e. with the frame of reference fixed in relation to the robot), or

ii)"observer-based" (i.e. with the frame of reference fixed in relation to the observer).

In this experiment, the subjects used different frames of reference for different joints. All subjects used a robot-based method for joint 1, but only 8/12 subjects used a robot-based method for joints 2 and 3. The remaining 4 subjects used an observer-based method.

Unfortunately, due to the fact that too many sub-groups had been created within each classification (i.e. differences in terminology and reference points), there were not enough subjects in each group to allow for re-analysis of the data. However, interpretation of the results on an individual basis could still be made.

Referring back to Figure 6.5, subjects 1 and 5 made virtually 100% direction errors with both pendants and these subjects were found to have given consistent descriptions of the same moves from all orientations. They had selected a control-motion relationship for the +/- controls that was the complete reversal of that actually used for the PUMA robot, but they were consistently incorrect. Subjects 11 and 12 had also been consistent in their descriptions but they had chosen the correct control-motion relationship for joint 1 but incorrect for joints 2 and 3 and therefore made approximately 60% errors. Subjects 4,6,8 and 10 were correct for joints 2 and 3 but were incorrect on joint 1 and therefore made approximately 30% direction errors. All of these subjects, therefore, may not have selected the controls incorrectly if they had been trained or if they had received some feedback of the correct control-display relationship. The subjects of major interest in this experiment were 2,3,7 and 9 who had been inconsistent in their description of moves when viewing the robot from different positions, as they had used an "observer-based" frame of reference. These subjects made correct selections from the left side and back of the robot but made direction errors from the front and right side. Subject number 3 also accounted for almost all of the control errors made with the joystick.

C. Assessment of stereotype associations

The effect of these descriptions on control selection could be measured according to expected stereotypes. Table 6.10 shows the number of times that the +ve and -ve controls were selected when certain descriptive terms were given. It can be seen that there were strong stereotype associations between perceived motion and control selection (c. 90%), so strong in fact that it was not necessary to perform a statistical analysis on these results. This shows that the subjects' descriptions directly influenced their selection of controls. Thus the the differences in subject performance patterns (shown in Figure 6.5) were produced by the different ways in which they described the same movement (as the example in Table 6.9 shows).

Table 6.10 Description-control associations for all subjects using both teach controls.

Description of direction of movement	Control selected	
	+	-
right,clockwise,up,forward,towards	270 (90%)	30 (10%)
left, anticlockwise,down,back,away	22 (8%)	254 (92%)

D. Subject preferences

There was some difference in subject preference for the teach controls. Seven of the subjects (58%) said that they would prefer to use the joystick for control of robot motion but that they had found the toggle-switch easier to learn on. Two of the subjects preferred the toggle-switches and the remaining three subjects had no preference for either control.

6.2.3.2 Discussion

Although no statistical differences in control performance were obtained between any of the experimental conditions, important differences were observed between the individual subjects in their performance patterns. Examination of these patterns revealed different trends which were defined by three general factors;

1. The reference point chosen for motion direction established how a given movement would be described. For example, when motion of joints 2 or 3 was described according to the rotation terminology, the reference point could either be with the imaginary 'clockface' at the front or back of the robot. Thus, a movement of joint 2 in the positive direction may be described as 'clockwise' or 'anticlockwise' according to the reference point used.
2. The perceptual frame of reference used by the subject, irrespective of their description terminology, was either robot-based or observer-based. This factor determined whether or not the subject would be influenced by human-robot orientation in their description of joint movement.
3. In view of the strong association between perceived motion and control selection, the terminology used to describe joint motion determined whether a positive or negative control would be selected for a given joint movement. For example, if a movement of joint 2 in the positive direction was described as 'anticlockwise' the control '2-' would be selected, whereas if the same move was described as 'up' the control '2+' would be selected.

The combined effect of these factors created such diversity between the subjects in their performance patterns that reliable interpretation of the overall results was difficult if not impossible. Furthermore, due to the small subject sample used in the experiment the division of subjects into smaller groups made further statistical analyses impractical.

However, the high overall error rate obtained (c. 60%) does indicate that the majority of subjects did not perceive robot movement in the same way that the Unimate manufacturers have intended in their design for the PUMA anthropomorphic robot. This would suggest that the '+ve'/'-ve' controls used for labelling should be reversed on some joints. However, it seems that the solution is more complex as different subjects made control selection errors on different joints.

No particular differences were found between the teach pendant designs, because the subjects tended to describe the motion first and then look at the pendant for the appropriate control. However, there was a higher preference for the joystick control even though these subjects found the toggle controls easier to learn on.

6.2.4 Experiment 4: Perception of world movement and control selection at different human-robot orientations.

6.2.4.1 Results

A. Control selection

The error scores using each teach control are shown in Table 6.11. It can be seen that fewer errors overall were made compared to the joint mode experiment (25% for both teach boxes) and a greater proportion of those made were control errors, particularly when the robot was viewed from the front and back orientations.

Analysis 1. Total errors

The raw data for total error scores are given in Appendix IV.4i. As in experiment 2, because the raw data showed a large number of zero scores, the analysis was performed on transformed data (natural logarithm (x+1)). The analysis of variance table is given in Appendix IV.4ii. No significant difference was found in the total errors made with either teach control; $F(1,11) = 0.38$, $p=0.54$. However, there was a significant difference in the total errors made in different observer-robot orientations; $F(3,33) = 5.28$, $p=0.0044$. There was no significant interaction between the teach pendant used and orientation; $F(3,33) = 0.24$, $p=0.86$.

Table 6.11 Control selection errors at each human-robot orientation

a) Using Joystick pendant

	Human-robot orientation				
	FRONT	LEFT	RIGHT	BACK	TOTAL
Total no. of robot moves	72	72	72	72	288
Direction errors	10	10	11	6	37 (12.8%)
Control errors	15	4	6	13	38 (13.2%)
Total errors	25	14	17	19	72 (25%)

b) Using toggle switch pendant

	Human-robot orientation				
	FRONT	LEFT	RIGHT	BACK	TOTAL
Total no. of robot moves	72	72	72	72	288
Direction errors	10	9	19	10	48 (16.6%)
Control errors	14	1	0	9	24 (8.3%)
Total errors	24	10	19	19	72 (25%)

The mean error scores for the raw data and the transformed data at each orientation are shown in Table 6.12.

Table 6.12 Mean error scores at each human-robot orientation.

	FRONT	LEFT	RIGHT	BACK
mean	2.08	0.96	1.59	1.59
log mean	0.86	0.46	0.71	0.68

A Tukey test for comparison of means was carried out (as shown in Appendix IV.4iii). The only significant difference obtained was between the front and left orientations (p=0.01). Thus, the difference was due to the least number of errors being made at the left orientation (training position) and the highest being made at the front orientation.

Analysis of the data for type of errors made shows that a different distribution for each type was produced at each orientation. This is illustrated in Figure 6.6 and is discussed in separate analyses below.

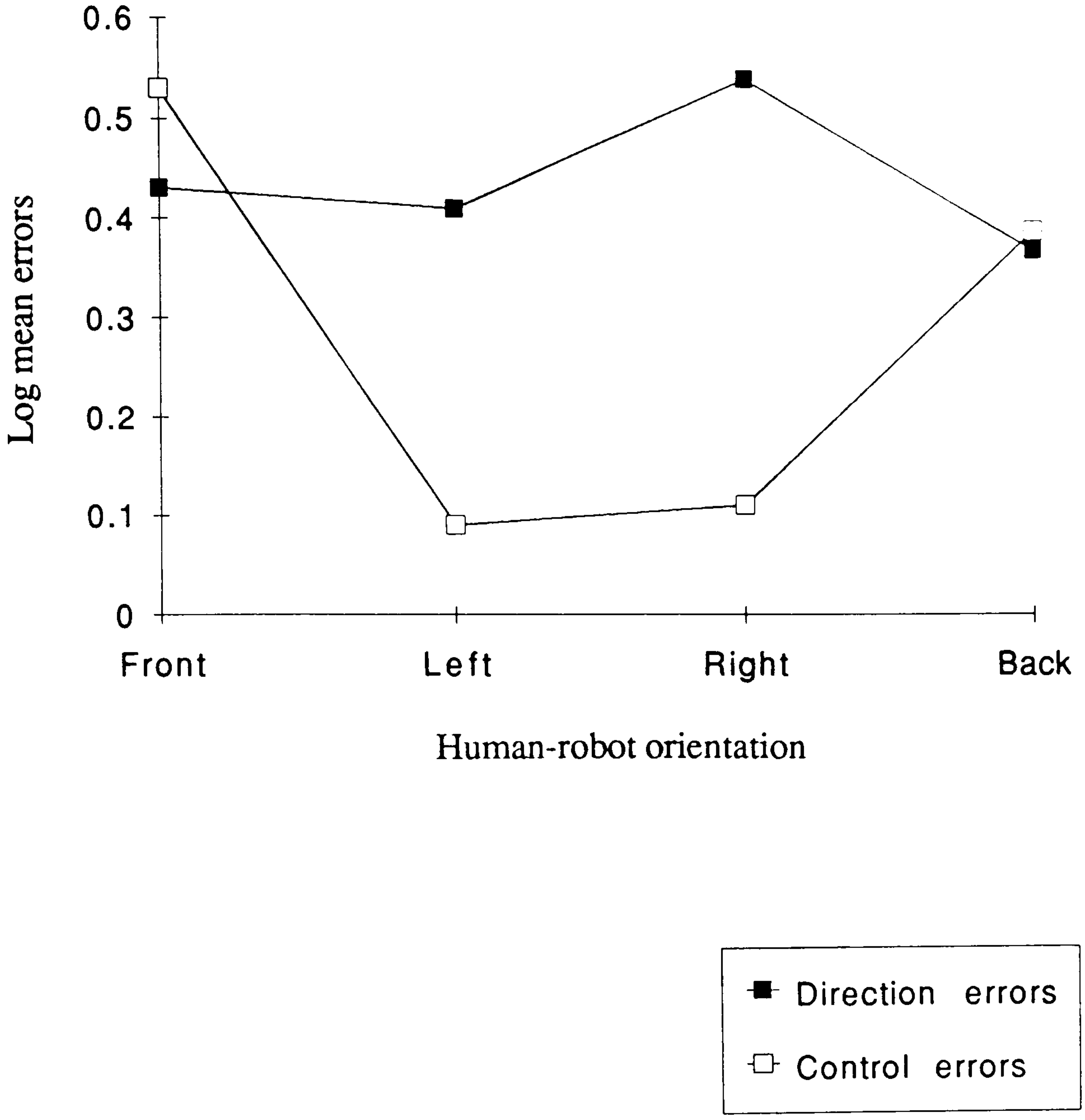
Analysis 2. Direction errors

The raw data for direction errors are given in Appendix IV.5i. Again, the analysis was performed on transformed data (natural logarithm (x+1)). The Analysis of Variance table is given in Appendix IV.5ii. There were no significant differences found on any of the factors.

Analysis 3. Control errors

The raw data for control errors are given in Appendix IV.6i. Again, the analysis was performed on transformed data (natural logarithm (x+1)). The Analysis of Variance table for control errors is given in Appendix IV.6ii. There was no significant difference between control errors made using either teach pendant; F(1,11) = 1.12, p=0.31, however there was a significant difference in the control errors made at different orientations; F(3,33) = 4.27,

Figure 6.6 Mean direction and control errors at each human-robot orientation



p=0.045. There was no significant interaction between teach pendant used and orientation; F(3,33) = 0.48, p=0.69. The mean error scores for the raw data and the transformed data at each orientation are shown in Table 6.13.

Table 6.13 Mean control errors at each human-robot orientation.

	FRONT	LEFT	RIGHT	BACK
mean	2.42	0.42	0.5	1.83
log mean	0.53	0.09	0.11	0.39

A Tukey test of comparison of means was carried out (as shown in Appendix IV.6iii). Significant differences were observed between the front orientation with the left and right orientations (p=0.05).

Due to the confounding influence of subject variability that was found in experiment 3, the individual subject performance patterns were also examined in this experiment. Figure 6.7 shows the proportion of responses for each subject that were; correct control selections, direction errors and control errors, using each teach control. It is immediately noticable that only some of the subjects were responsible for the errors made and, again, it was found that the subjects could be grouped according to their responses. As in experiment 3, the basis for grouping was similarity of performance on both teach controls as shown in Figure 6.8. The interpretation of these groups is again related to subject classification and this will be discussed in the next section.

Figure 6.7 Individual subjects' performance patterns using each teach control, showing the proportion of their responses that were; correct control selections, direction errors, and control errors

Figure 6.8 Individual subjects' performance data after grouping

B. Description of movement

As expected all the subjects used a linear movement terminology to describe the direction of motion along each axis. However, some of the subjects chose different reference points from which direction of motion was defined. The terminologies and reference points used for describing direction of axis motion are shown in Table 6.14. It can be seen that there was no ambiguity in describing motion along the Z axis; all the subjects described this as up/down in relation to the real world environment. For direction along the X and Y axes, all subjects used a linear motion terminology but differed in their selection of motion reference point. For example, subjects 4, 5, and 8 described axis motion as 'right/left' or 'forward/back' as it would appear from the front of the robot, whereas subjects 11 and 12 used the same descriptions but these related to how each movement would appear from behind the robot. The consequence of this was that the first group described a movement along the X axis in the positive direction as 'right' whereas the latter group described this movement as 'left'.

In addition the subjects differed in consistency of their descriptions of each movement when viewed from different orientations. Table 6.15 shows the descriptions given by all subjects for a movement along the X axis in the positive direction. Subjects 1, 4, 5, 8, 9, 10, 11 and 12 gave consistent descriptions from each orientation. The remaining subjects gave inconsistent descriptions when they viewed the movement from different orientations and these descriptions referred to how that movement 'appeared' at the time.

Thus, in this experiment also, the subjects had differed in their frame of reference for motion direction. As was found in experiment 3, these subjects could be classified in terms of their frame of reference for describing motion which were;

i) "robot-based" (i.e with the frame of reference fixed in relation to the robot), or

ii) "observer-based" (i.e. with the frame of reference fixed in relation to the observer).

In this experiment, the subjects also used different frames of reference for description of movement along different axes. All of the subjects used a robot-based method for motion along the Z axis, but only 8/12 subjects used a robot-based method for axes X and Y. The remaining 4 subjects used an observer-based method.

Table 6.14 Terminologies used for describing direction-of-movement along each axis and the reference points from which directions were related

AXIS	TERMINOLOGY	REFERENCE POINT	NO. SUBJECTS	SUBJECTS
X & Y	forward/back	centre of robot, outwards	3	1,9,10
	right/left, forward/back	back view of robot	2	11,12
	right/left, forward/back	front view of robot	3	4,5,8
	right/left, towards/away	current view of subject	4	2,3,6,7
Z	up/down	the world environment	12	ALL

Table 6.15 Subjects' descriptions of the axis X movement in the positive direction when viewed from different human-robot orientations

Subject	Human-robot orientation			
	FRONT	LEFT	RIGHT	BACK
1	forward	forward	forward	forward
9	forward	forward	forward	forward
10	forward	forward	forward	forward
4	right	right	right	right
5	right	right	right	right
8	right	right	right	right
11	left	left	left	left
12	left	left	left	left
2	left	towards	away	right
6	left	towards	away	right
7	left	towards	away	right
3	left	away	towards	right

As in experiment 3, there were not enough subjects in each group to allow for adequate statistical re-analysis of the data and so interpretation of the results was again made on an individual basis.

Referring to Figure 6.8, subjects 1, 4, 5, 8, 9 and 10 made virtually no control selection errors; these subjects had used a robot-based frame of reference and their chosen reference point was either from the front of the robot (subjects 4, 5 and 8), or the centre of the robot outwards (subjects 1, 9 and 10). The remaining two subjects classified as robot-based (subjects 11 and 12) made correct control selections for axis Z movement, but virtually 100% direction errors for axes X and Y. These subjects had used the back view of the robot for their reference point and therefore had initially established an incorrect control-motion relationship and had consistently maintained this relationship throughout the experiment.

Four subjects were classified as observer-based and their pattern of results was much more erratic (subjects 2, 3, 6 and 7). As subjects 3, 6 and 7 had been consistently correct in their description of axis Z movement, at least 30% of their responses were correct. Subject 2 had reversed the description-control association for axis Z movement using the toggle pendant only. The observer-based subjects produced a distinctive pattern of responses for X and Y axes movements; they made direction errors at the right orientation (opposite to the training condition) and control errors at the front and back orientations.

C. Assessment of stereotype associations

The association between the subjects' description of axis movement and control selection was examined for evidence of stereotyping. Table 6.16 shows the number of times that the +ve and -ve controls were selected for each of the descriptive terms used.

Again, it appears that there was a strong stereotype association between perceived motion and control selection, and again this was so strong that statistical analysis was not necessary.

Table 6.16 The description-control associations for all subjects using both teach controls

Description of direction of movement	Control selected	
	+	-
up,forward,towards	272 (92%)	24 (8%)
down,back,away	29 (11%)	244 (89%)

D. Subject preferences

There was a difference in subject preferences for the teach controls in this experiment. Six of the subjects (50%) preferred the joystick as they said it was more compatible with robot movement and could be orientated to match each movement. However, five of the subjects did not like the joystick as they found that the X and Y relationship did not remain consistent when viewed from different orientations, and the rotation control (axis Z) was confusing. These subjects preferred the toggle-switch pendant as it had a more logical, consistent arrangement and the +ve/-ve directions were easy to understand. The remaining subject had no preference for either control as he found that the difficulty of the task had been working out what the move of the robot was, not finding an appropriate control.

6.2.4.2 Discussion

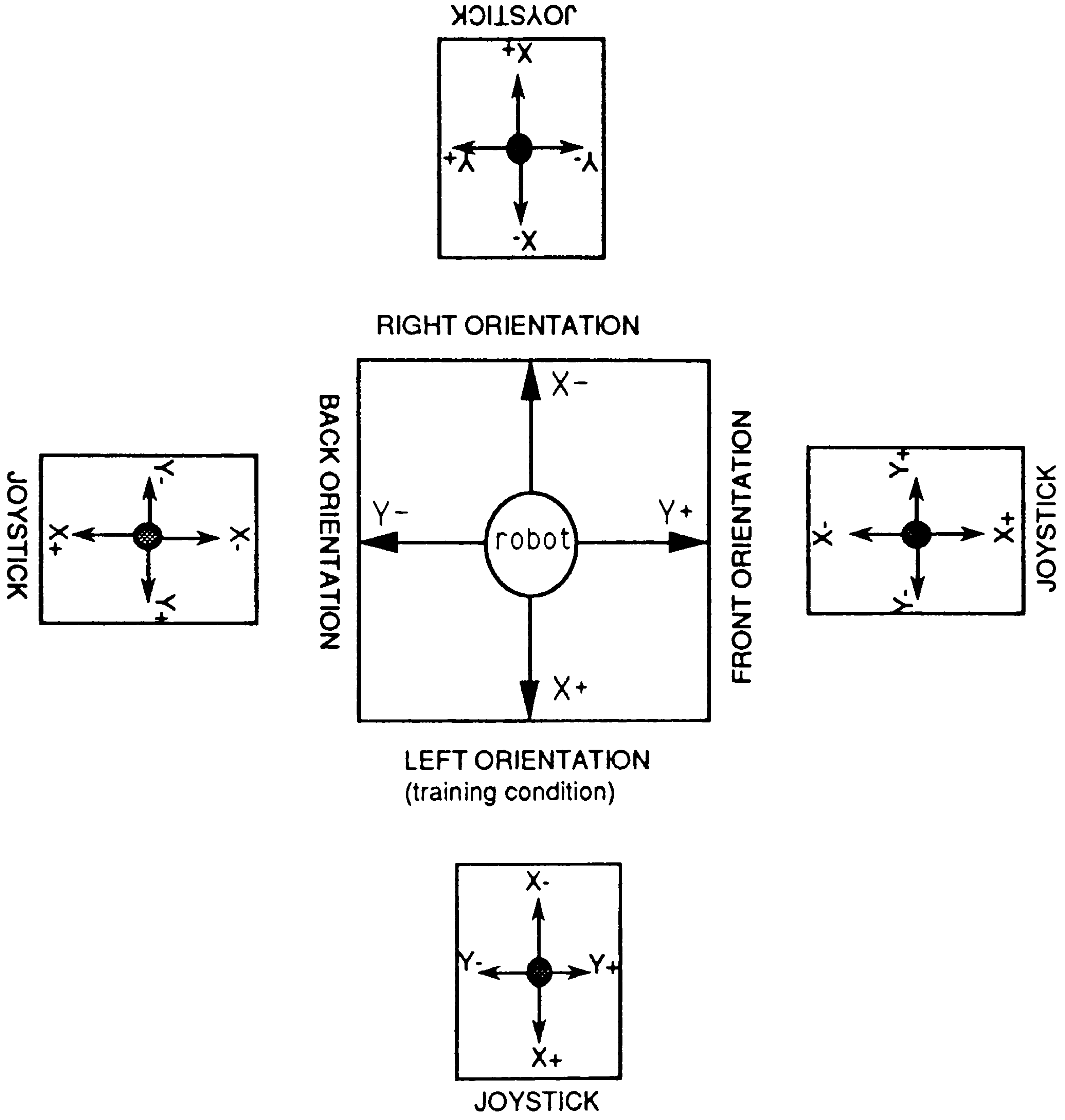
Analysis of individual subjects' performance patterns in the world mode experiment revealed some variation but not as much as in the joint mode experiment. The subjects all used the same type of direction terminology (i.e according to linear movement), but differed in their frame of reference used (i.e robot-based or observer-based), and the reference point chosen for description of X and Y directional movement. Four of the subjects used an observer-based frame of reference and these produced a distinct pattern of error performance related to their expectation that the control-motion relationship would always be compatible with their current view of the robot regardless of the human-robot orientation. Since the joystick has physical resemblence to robot motion along the X and Y axes, this can be illustrated by showing the changes in control-motion relationship that occur when the joystick is used from each orientation. Figure 6.9 shows how, in experiment 4, the direction of joystick movement along the X and Y axes was compatible with robot movement from the left side (i.e. the training condition), but was incompatible with robot movement at all other orientations.

It can be seen that at the left orientation (the training condition) joystick motion exactly matches the direction of robot motion along the X and Y axes and the subjects made correct control selections at this position. At the right orientation the joystick controls still match their corresponding axes (e.g. X moves forward and back, Y moves from side to side), but the direction of movement is reversed (e.g. the 'X+' control moves the robot towards the subject), therefore the subjects made direction errors at this position. At the front and back orientations the joystick controls no longer match their corresponding axes (i.e. movement of the joystick along the X axis resembles robot movement along the Y axis and vice-versa), which caused the observer-based subjects to make control errors.

To some extent this effect was observed in the initial experimental analyses depicted in Figure 6.6. There was a significant increase in control errors at the front and back orientations and, although not significant, there were more direction errors made at the right orientation. The significant increase in control errors at the front and back orientations was almost entirely due to the four observer-based subjects as few errors had been made by the robot-based subjects (see Figure 6.8). These subjects also accounted for most of the direction errors made at the right orientation, although this did not produce a significant result as it was offset by the two robot-based subjects who had made direction errors in all orientations (Figure 6.8, subjects 11 and 12). This also explains the lower error rate observed in the world mode experiment compared to the joint mode experiment (25% to 64% respectively) as the errors were produced by only six subjects.

As was found in the joint mode experiment there was no significant difference in error performance using either teach box. Again this was most likely because the subjects tended to describe motion first and then select the appropriate control from the teach box which, in turn, may have produced the strong relationship between perceived motion and control selection.

Figure 6.9 Changes in the control-motion relationship when the joystick experimental teach box was used at different human-robot orientations



6.2.5 Re-interpretation of experiment 2

In the light of the findings of the experiments in stage 2, it is necessary to reassess the results of experiment 2 from stage 1. It had been assumed that the linear movement terminology group perceived robot motion in relation to themselves (i.e. they used an 'observer-based' frame of reference) and the rotation terminology group used a 'robot-based' frame of reference. However, the results of experimental stage 2 have shown that a subject can be either observer-based or robot-based irrespective of the terminology they use to describe direction-of-movement. It is 'consistency' of direction-of-movement description that is now used to define the use of a robot-based perceptual frame of reference, previously described in section 6.2.3.1, B.

The data for the individual subjects in experiment 2 were thus re-examined to look for consistency in their descriptions of joint motion when viewed in different configurations. All of the subjects in the linear movement group had, in fact, used the observer-based method for describing joint motion as was demonstrated by their inconsistent descriptions of each movement when the robot arm-configuration had changed. In the rotation terminology group, however, four of the subjects had used a robot-based frame of reference and the remaining six had used an observer-based frame of reference. As an example, the descriptions given for a movement of joint 2 in the positive direction by all of the subjects are shown in Table 6.17.

Performance was measured in terms of description consistency with that provided in the training condition (configuration A). The appearance of the joint 2+ movement was 'up' for the linear movement group and 'anti-clockwise' for the rotation terminology group. It can be seen that all of the subjects using the linear movement terminology gave consistent descriptions of that movement in configurations A and B (i.e. the RIGHTY-arm configurations) but inconsistent descriptions in configurations C and D (i.e. the LEFTY-arm configurations). Within the rotation terminology group all of the subjects had given consistent descriptions of the movement in configuration A, however there was some variation between the subjects in their descriptions of the movement in other configurations. Four of the subjects (7, 9, 12 and 18) gave consistent descriptions in all four configurations, indicating the use of the 'robot-based' frame of reference. Subjects 4, 5, 10 and 11 gave inconsistent descriptions when the

Table 6.17 Subjects' descriptions of a joint 2 movement in the positive direction when viewed in different robot arm-configurations

Subject	Robot arm-configuration			
	A	B	C	D
7	ac	ac	ac	ac
9	ac	ac	ac	ac
12	ac	ac	ac	ac
18	ac	ac	ac	ac
2	ac	cw	cw	ac
19	ac	ac	cw	cw
4	ac	cw	ac	cw
5	ac	cw	ac	cw
10	ac	cw	ac	cw
11	ac	cw	ac	cw
1	up	up	down	down
3	up	up	down	down
6	up	up	down	down
8	up	up	down	down
13	up	up	down	down
14	up	up	down	down
15	up	up	down	down
16	up	up	down	down
17	up	up	down	down
20	up	up	down	down

robot arm had rotated (configurations B and D). The two remaining subjects gave confusing results which did not match the expected descriptions for use of either the 'robot-based' or 'observer-based' frames of reference.

Thus, the trends previously identified in the original interpretation of experiment 2, previously indicated in Figure 6.3, were caused by most of the subjects using an 'observer-based' frame of reference. However, the less marked trend for the rotation terminology group was due to the four subjects within that group who were using a robot-based frame of reference.

The data for these four subjects were removed and the results were re-analysed. The mean errors for each group are shown in Table 6.18.

The raw data for the re-analysis are given in Appendix IV.7i. The Analysis of Variance table is given in Appendix IV.7ii. The overall results remained the same although there were slight differences in the F-values for each factor. For the main effect of a difference in performance between each subject group the F-value was reduced (first analysis, F(1,18) = 21.51, p=0.0002, re-analysis, F(1,14)=12.49, p=0.0033). Thus there was a reduced effect of group on direction error performance. For the main effect of robot configuration the F-value was also reduced (first analysis, F(3,54) = 26.31, p=0.0000, re-analysis, F(3,42)=18.39, p=0.0000) indicating a reduced effect of configuration on error performance.

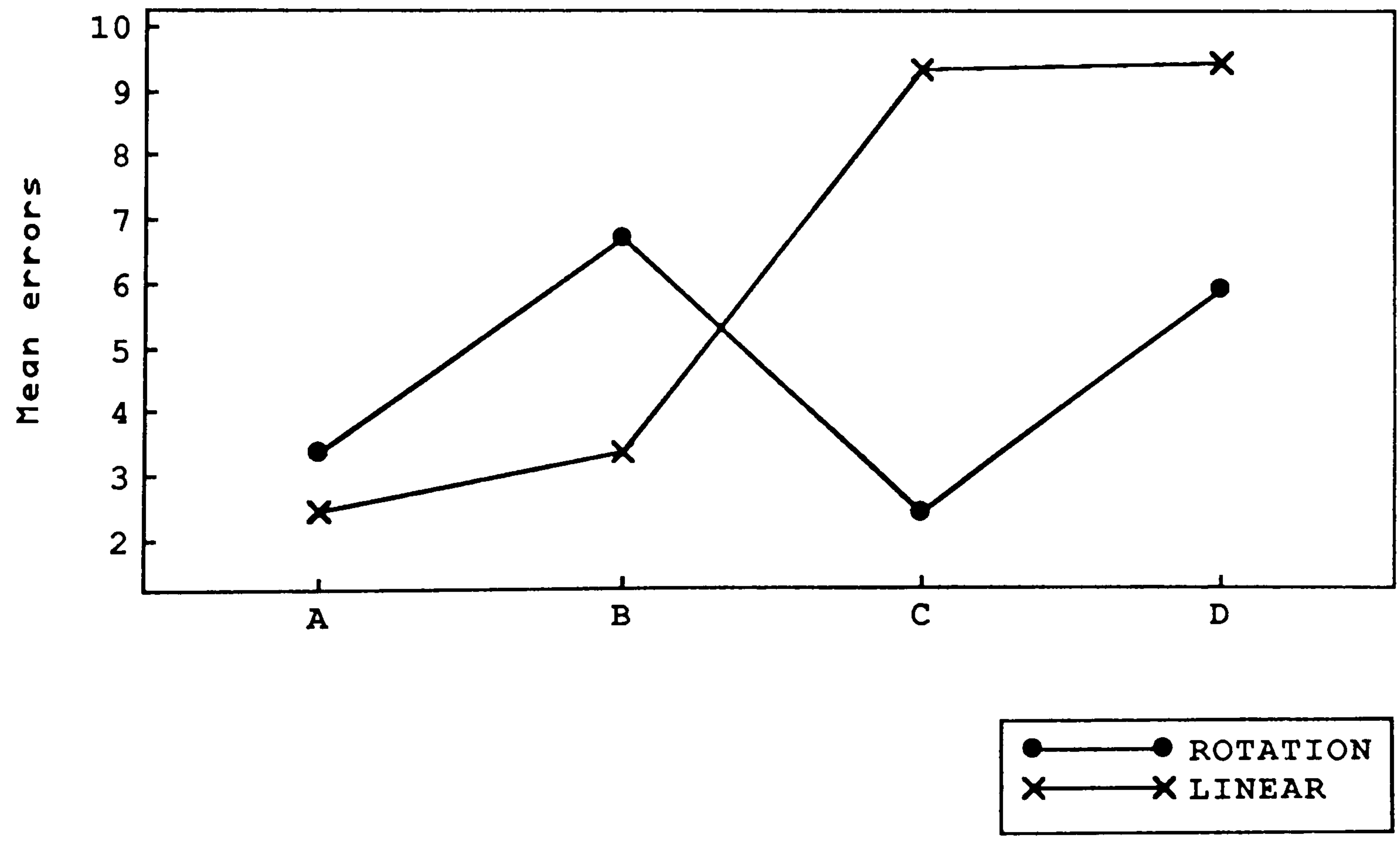
For the interaction between subject group and robot configuration the F-value was also reduced (first analysis, F(3,54) = 28.12, p=0.0000, re-analysis, F(3,42)=25.15, p=0.0000). This interaction is shown in Figure 6.10 and it can be seen that the effect of removing the four 'robot-based' subjects from the rotation terminology group has been to increase the mean errors at configurations B and D.

Assessment of the simple main effects, as shown in Appendix IV.7iii, also produced different results. In the first analysis, significant effects of terminology group had been identified at configurations C and D but not configurations A and B. In the re-analysis significant effects were identified at B, C and D. Again the effect of configuration at both

Table 6.18 Mean error scores of joint movement descriptions for observer-based subjects in each terminology group at each robot arm-configuration

Terminology group	Robot arm-configuration				Overall mean	% error rate
	A	B	C	D		
rotation	3.3	6.6	2.3	5.8	4.5	37.5
linear	2.4	3.3	9.3	9.4	6.1	50.8
Overall mean	2.8	4.9	5.8	7.6		
% error rate	23	41	48	63		

Figure 6.10 Mean errors in direction-of-movement descriptions made by observer-based subjects in each terminology group at each robot arm-configuration



groups was found to be significant; rotation terminology group, F(3,42) = 7.9, p=0.000; linear movement group, F(3,42) = 44.9,p=0.000.

A Tukey test for comparison of means within each terminology group (shown in Appendix IV.7iv) indicated the same results as the first analysis for the linear movement terminology group; that the means for configurations C (9.3) and D (9.4) were significantly different from those at configurations A (2.4) and B (3.3), p=0.01. Within the rotation terminology group, however, the same results were not obtained; significant differences were identified between the mean at configurations B (6.6) with those at configurations A (3.3) and C (2.3) and between the mean at configuration C (2.3) with those at configurations B (6.6) and D (5.8), p=0.01. However, in the re-analysis, no difference was identified between the means at configuration A (3.3) with configuration D (5.8).

These results confirm the earlier conclusion that, for subjects who use an observer-based frame of reference, the terminology used to describe direction of joint motion will produce different types of 'misperception' depending upon the type of change in robot arm-configuration that occurs. Namely, subjects who use a rotation terminology may misperceive joint motion when their view of the robot is rotated (i.e positions B and D shown in Figure 5.9). However, this trend has not been found amongst all of the subjects classified as 'observer-based' within this group. For example, subjects 2 and 19 did not make misperceptions according to this pattern (see Table 6.17). Consequently the trend has been produced by only four subjects and therefore the results of subjects 2 and 19 may have influenced the mean error scores.

All subjects who used a linear motion terminology, on the other hand, misperceive joint motion when the robot arm moves into a different configuration (i.e positions C and D shown in Figure 5.9).

6.3 Stage 3: Direct control performance

At this stage of the experimental programme an interfacing technique had been developed which enabled direct control of robot motion using either of the mock-up teach controls. Thus it was now possible to examine actual control performance in a more realistic fashion, where feedback through observation of robot motion was available.

In view of the influence of subjects' perceptual frame of reference found in the previous stage (i.e. 'robot-based' or 'observer-based', previously described in section 6.2.3.1), together with the further influence of terminology on observer-based subjects (i.e. rotation or linear movement), subjects were classified according to their description of robot movement before the experimental task began. It was hoped that a reasonable sample for each of the groups (robot-based, observer-based rotation, and observer-based linear) would be produced, and hence, a reasonably large subject population was required. After screening for their classification group, the subjects were given a performance task in which they were provided with instructions to move the robot arm in a specified manner and for a specified task as quickly but as accurately as possible. Each task was carried out twice by each subject, using each teach box once. In order to eliminate the confounding effect produced by subjects selecting different reference points for directional motion in experiments 3 and 4, all training was carried out from the front orientation.

Two experiments were carried out in this stage, in order to examine control performance in Joint and World programming modes. Due to restrictions of time and laboratory space the joint mode experiment only included changes in robot arm-configuration with the subject remaining at the front orientation as in experiments 1 and 2. In the world mode experiment the task was performed at only three human-robot orientations (front, back and right side). As the training position was now at the front of the robot for both experiments the joystick labelling was adjusted so that it was compatible with robot movement when viewed from the front orientation (see Figure 5.15, described in section 5.3.4).

Measures of both time and accuracy were taken, so in each experiment the following null hypotheses were examined;

Performance accuracy

Ho1: There will be no differences in errors made between each subject group.

Ho2: There will be no differences in errors made using either teach box.

Ho3: There will be no differences in errors made at each orientation/configuration.

Ho4: There will be no interactions between any of these factors.

Response time

Ho5: There will be no differences in response times between each subject group.

Ho6: There will be no differences in response times using either teach box.

Ho7: There will be no differences in response times at each orientation/configuration.

Ho8: There will be no interactions between any of these factors.

The procedure for each experiment was different and so they will be presented separately.

6.3.1 Experiment 5: Control performance in joint mode

6.3.1.1 Procedure

The subject was seated directly in front of the robot and remained in this position throughout the experiment. The robot was initially in the 'READY' position. The subject was shown how each of the joints could be moved (i.e. joints 1,2 and 3 were moved in each direction). In the same way as in the previous experiments, the experimenter indicated the joint number but gave no verbal label to directional movements.

A. Subject classification

In this experiment two methods of subject classification were used; one which involved the subjects' description of the moves they saw (as had been used in the previous experiments), and another which involved identification of the same move when viewed in different robot configurations. The introduction of a new method was partly an attempt to verify the first method and also to try and find a quicker way of classifying subjects.

Method 1. Description of movement

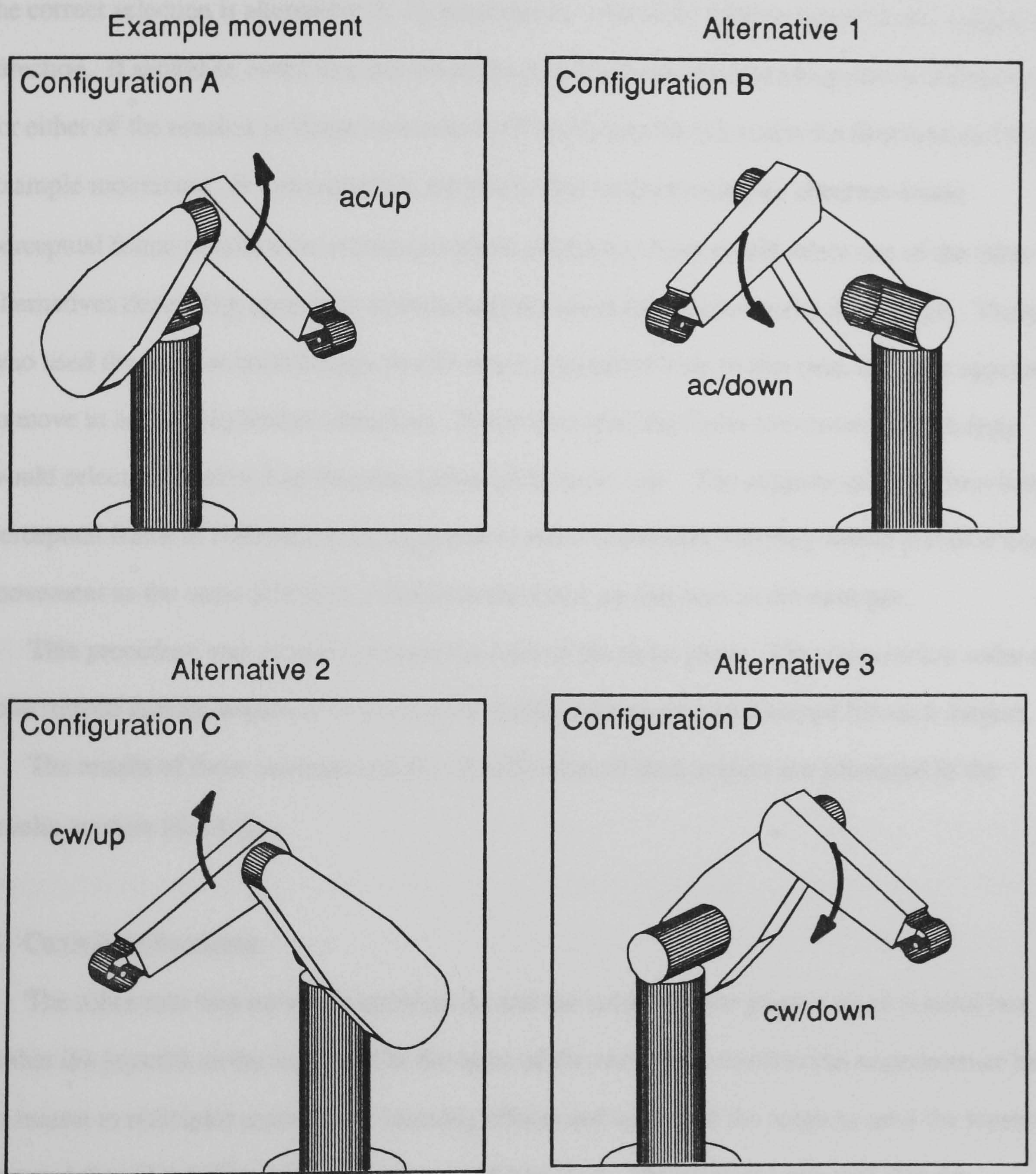
The robot was moved to configuration A (previously shown in Figure 5.9). Each of the three joints were moved individually in each direction (+ve, -ve). After each move the subject was asked to describe the move in terms of the joint that had moved and the direction it had moved in. The subject was then told that they had completed a practice of the first part of the task in order to familiarise themselves with the task. In fact, the practice task was used in order to establish the subjects' perceptual reference points under the 'normal' robot configuration. The robot was then moved to one of the four configurations (A, B, C, D) shown in Figure 5.9 for the actual description task. Exactly as before, each joint was individually moved in each direction and the subject described each move.

The subjects were classified according to the pattern of responses they gave. If their description of each actual move when viewed in different configurations was consistent with their description of it during the practice task, they were classified as using a robot-based frame of reference. If, however, their descriptions were inconsistent, they were classified as using an observer-based method. The terminology used to describe direction of motion was also recorded for further classification of observer-based subjects.

Method 2. Movement identification

The subject was told that the robot arm would be moved to any of the four start configurations they had just seen. From this position only one joint movement would then be made. (i.e. one joint, moving in one direction only). The subject was asked to observe this move carefully and remember it. The robot arm was then moved to each of the three remaining start configurations from which a single movement of the same joint was made. The subject was required to choose from the last three moves, the one that was exactly the same joint movement as the example that they had been asked to remember. The choice of moves were arranged such that they represented the expected selection of each of the three possible subject classification groups; robot-based, observer-based rotation terminology and observer-based linear movement terminology. An example of one joint movement and the expected responses for each classification group is shown in Figure 6.11.

Figure 6.11 Subject classification method 2; an example of the task for identifying a movement of joint 3 in the positive direction



It can be seen in Figure 6.11 that the example movement, which was always given with the robot arm in configuration A, for joint 3 moved in the positive direction appears to move the joint 'anticlockwise' or 'up'. The subjects were required to select from the three alternative movements the one which moved the joint in the same direction as in the example. In this case the correct selection is alternative 3. In alternatives 1 and 2 the joint is moved in the negative direction. It should be noted that the direction-of-movement descriptions given in alternative 3 for either of the rotation or linear movement terminologies do not match the descriptions for the example movement. It was expected, therefore, that subjects using an observer-based perceptual frame of reference would not select alternative 3 but would select one of the other alternatives depending upon their terminology for direction-of-movement description. Those who used the rotation terminology would select alternative 1 as, in this case, the joint appeared to move in an 'anticlockwise' direction. Those who used the linear movement terminology would select alternative 2 as the joint appeared to move 'up'. The subjects using a robot-based perceptual frame of reference were expected to select alternative 3 as they would perceive this movement as the same direction, relative to the robot, as that seen in the example.

This procedure was carried out once for each of the three joints. The presentation order of joint moved and the sequence of alternative configurations was randomised for each subject.

The results of these methods and the classification of each subject are presented in the results section (6.3.1.3).

B. Control performance

The robot arm was moved to position A, and the subjects were given a teach control box (either the joystick or the toggle). On the basis of the earlier experiments the experimenter had no reason to anticipate asymmetric learning effects and so half of the subjects used the joystick first and the other half used the toggle control box first. The subjects were told that the controls on the control box could be used to move the robot joints in the same way that they had just seen. They were then given time to try out the controls and familiarise themselves with the control-motion relationship. This was an unlimited time, lasting until the subject stated that they understood the control-motion relationship; in general, this took no more than 3 minutes.

During the experimental task the robot was moved to one of the start configurations (A, B, C or D) and the subject was then given a movement instruction. To avoid the ambiguity associated with verbal description, these were given as written instructions containing joint numbers (1,2 or 3) and direction arrows (↑,↓, ← or →). Each instruction was projected onto a screen (as shown in Figure 5.18, described in section 5.3.7) and the subject was required to move the robot accordingly as quickly as possible. Response time was measured from the moment of the instruction being presented to activation of a control on the teach box.

A practice trial was carried out with the robot in the training position (configuration A). The instruction was presented by placing a transparency onto the overhead projector and switching the power to the projector on. Timing of the subjects' responses was initiated by the input switch being simultaneously released with the projector power switch, and was completed as soon as a control on the teach box was selected. The resulting robot movement was recorded by the experimenter. Three separate instructions were given (one for each joint) in each configuration. This constituted the experimental task and the subject was told that this would be repeated several times, and that the robot would be moved to a new position before each task. There were eight possible start configurations (each of the four configurations A, B, C and D plus the same configurations with the robot gripper at the rear of the robot's work envelope). The experimental task was carried out twice from each configuration. Thus, each subject moved each joint sixteen times, making a total of forty-eight moves altogether. The order of presentation of each task was randomised and the order of control instructions for each configuration was also randomised. Each subject performed the entire experiment. When all sixteen tasks had been completed the first session of the experiment was ended. The subjects agreed to attend one week later for the second session.

When the subject returned they were again seated at the front of the robot. They were given a different control box (i.e. not the one they had used in the first session). The robot was moved to configuration A (the training position) and the subject was again given time to practice with the teach box and learn the control-motion relationship. When they were familiar with this, the practice task was performed and then the experiment began. The experimental task was exactly the same as in the previous session and was performed in the same order as before for each subject. This was so that performance between each teach control could be compared directly without concern for the effect of presentation order.

When all sixteen tasks had been completed the initial movement identification task was repeated. This was to see whether performance of the control task with feedback from robot movement may have altered any of the subjects' perceptual reference frames.

When the experiment was finished, the subject was given a question sheet for their comments on the experiment and the teach controls they used. The subjects were asked to mention any strategies they had developed to help them perform the task and for their opinions of the teach control designs.

6.3.1.2 Design

Fifteen undergraduate students, 8 males and 7 females took part in the experiment. The experiment consisted of two 1-hour sessions and the subjects were paid £8 on completion of the second session.

For analysis of control performance a three factor (2 x 2 x 4) ANOVA with repeated measures design was used in order to assess the effect of these factors on subject performance.

The factors were defined by;

a) subject group (robot-based and observer-based)

b) teach control used (joystick and toggle)

c) robot arm configuration (A, B, C, D)

Subjects' performance was evaluated by;

i) correct or incorrect joint movement where an incorrect response was defined as being either;

a) control error, or

b) direction error

ii) response time (i.e. the duration between the presentation of the move instruction and the selection of a control on the teach box)

Thus, four analyses of the results were carried out;

Analysis 1. Total errors

Analysis 2. Direction errors

Analysis 3. Control errors

Analysis 4. Response time

An instruction for each joint movement was given from each position (A, B, C and D) twice, making a total of forty-eight discrete movements. The presentation order of start positions and movement instructions was randomised for each subject. Each subject repeated the whole experiment one week later using the other teach control box.

On the basis of the findings of the previous experiments, it was expected that subjects using a robot-based frame of reference would make fewer errors than those using an observer-based frame of reference. Furthermore, the observer-based subjects who used rotation terminology for motion description would make direction errors when the robot was rotated (e.g. positions B and D in Figure 5.9), whereas the observer-based subjects who used linear movement terminology for motion description would make direction errors when the robot arm-configuration changed (e.g. positions C and D).

6.3.1.3 Results

A. Subject classification

The results of each classification method are shown in Table 6.19. It can be seen that for description of joint movement (method 1), five subjects used a rotation terminology, seven used linear movement and three used a mixed terminology (rotation for joint 1 and linear movement for joints 2 and 3). Four of the subjects using the rotation terminology and two of those using the linear movement terminology had described joint movement consistently regardless of arm-configuration and were therefore classed as using a robot-based frame of reference (subjects 1,2,4,10,14,15). All of the other subjects had described joint movements inconsistently in accordance with the patterns of misperception previously found in experiment

Table 6.19 Subject classification for experiment 5

Subject	Method 1: Description		Method 2: Identification		Final Classification
	Terminology	Frame of Reference	Frame of Reference	Proportion of responses	
1	linear	R-B	R-B	3/3	R-B
2	rotation	R-B	R-B	3/3	R-B
3	linear	O-B	O-B	2/3 joint 1	O-B
4	linear	R-B	R-B	2/3 joint 2	R-B
5	linear	O-B	O-B	3/3	O-B
6	linear *M	O-B	O-B	2/3 joint 1	O-B
7	linear *M	O-B	R-B	3/3	R-B
8	linear	O-B	O-B	2/3 joint 3	O-B
9	linear	O-B	O-B	3/3	O-B
10	rotation	R-B	R-B	2/3 joint 3	R-B
11	linear *M	O-B	R-B	3/3	R-B
12	linear	O-B	O-B	2/3 joint 1	O-B
13	rotation	O-B	O-B	2/3 joint 1	O-B
14	rotation	R-B	R-B	3/3	R-B
15	rotation	R-B	R-B	3/3	R-B

*M = mixed terminology (rotation for joint 1, linear movement for joints 2 and 3)

R-B = robot-based

O-B = observer-based

2 (i.e. rotation descriptions were inconsistent when the robot was rotated and the linear movement descriptions were inconsistent when the arm-configuration had changed). According to classification method 1 therefore, these nine subjects were classed as using an observer-based frame of reference (subjects 3,5,6,7,8,9,11,12,13).

For identification of joint movement (method 2) most of the subjects had made the expected choices corresponding with their classification by method 1. However, there were some incongruent choices made and the criteria for subject classification in method 2 was based on the majority of choices (i.e. at least 2/3 were of the same type). Table 6.19 also shows the proportion of choices within the classification type given by each subject and, where this was not 3/3, the joint on which an incongruent choice had been made. Only two of the subjects were classified differently by method 2 than by method 1 and both of these subjects had been classed as observer-based using mixed terminology in method 1 but made 3/3 robot-based choices in method 2 (subjects 7 and 11). As the selection of 3 consistent robot-based choices in method 2 would require a more comprehensive understanding of actual robot movement, the final classification of these two subjects was robot-based.

By the final classification, then, eight subjects were placed in the robot-based group and seven were placed in the observer-based group (see Table 6.19). As all but one of the observer-based subjects had used a linear movement terminology for motion description (subject 13), no further grouping of terminology was made.

The experimental results were compared for the two groups; robot-based and observer-based linear movement terminology.

The movement identification task (method 2) was repeated after the experimental task had been completed (i.e. at the end of the second session). This was to see if any of the subjects' perceptual reference frames had altered after performing the experiment. The pre-experiment and post-experiment results are shown in Table 6.20. It can be seen that, using the criterion for classification previously described for this method (i.e. at least 2/3 choices must be of the same type), four of the seven subjects that were initially classed as 'observer-based' were classed as 'robot-based' in the post-experiment task (subjects 3, 8, 12 and 13). This finding suggests that these subjects altered their frame of reference at some time during the experiment.

Table 6.20 Subject classification by method 2 (joint identification) before and after performing the experimental task

Subject	Pre-experiment		Post-experiment		changes
	Frame of Reference	Proportion of responses	Frame of Reference	Proportion of responses	
1	R-B	3/3	R-B	3/3	
2	R-B	3/3	R-B	3/3	
3	O-B	2/3 joint 1	R-B	3/3	O-B --> R-B
4	R-B	2/3 joint 2	R-B	2/3 joint 2	
5	O-B	3/3	O-B	2/3 joint 1	
6	O-B	2/3 joint 1	O-B	3/3	
7	R-B	3/3	R-B	3/3	
8	O-B	2/3 joint 3	R-B	2/3 joint 1	O-B --> R-B
9	O-B	3/3	O-B	3/3	
10	R-B	2/3 joint 3	R-B	3/3	
11	R-B	3/3	R-B	3/3	
12	O-B	2/3 joint 1	R-B	2/3 joint 3	O-B --> R-B
13	O-B	2/3 joint 1	R-B	3/3	O-B --> R-B
14	R-B	3/3	R-B	3/3	
15	R-B	3/3	R-B	3/3	

R-B = robot-based

O-B = observer-based

This may have influenced the between-group results which will be discussed later in section 6.3.1.4.

B. Control performance

Analysis 1. Total Error scores

At the first level of analysis, a three factor (2 x 2 x 3) repeated measures ANOVA was carried out on total error scores. Although there were a few zero scores in the data it was decided that there were not enough to require transformation of the data (the raw data is given in Appendix IV.8i). The mean error scores for each subject group using each of the teach boxes are shown in Table 6.21. The Analysis of Variance table is given in Appendix IV.8ii. Although there was a difference in error scores between each group (21% R-B, 33% O-B), this was not significantly different; F(1,13) = 3.48, p=0.0849. There was no significant difference between the errors made with each teach control box, F(1,13) = 3.675, p=0.0775.

There was a significant difference in the error scores made in each of the robot configurations, F(3,39) = 7.163, p=0.0006. The mean error scores are shown in Table 6.22. It can be seen that the error scores were similar in positions A and B ('RIGHTY' arm configuration) as were those in positions C and D ('LEFTY' arm configuration). A Tukey test for comparison between means identified significant differences between configuration B (2.3) with C (3.9) and D (3.8), p=0.01 and between configuration A (2.75) with C (3.9), p=0.05 (see Appendix IV.8iii). However a less stringent comparison of means test (Newman-Keuls) also identified a significant difference between configuration A (2.75) with D (3.8), p=0.05 (see Appendix IV.8iv).

There were no statistically significant interactions between any of these factors. However, the group-configuration interaction is worth investigating as it may have been significant with a larger sample; F(3,39) = 2.683, p=0.0599, and it was expected that the subject groups would perform differently as a result of robot arm-configuration changes.

Assessment of the simple main effects indicated that there were no significant effects of group at any of the configurations (see Appendix IV.8v). The effect of configuration at the

Table 6.21 Mean error scores for each subject group using each teach control

Subject group	Teach control		Overall mean	% error rate
	Joystick	Toggle-switch		
Robot-based	2.9	2.03	2.47	20.6
Observer-based	4.32	3.57	3.94	32.8
Overall mean	3.61	2.8		
% error rate	30.1	23.3		

Table 6.22 Mean error scores for each subject group in each robot arm-configuration

Subject group	Robot arm-configuration					
	A	B	C	D	Overall mean	% error rate
Robot-based	1.93	2.25	2.68	3.0	2.46	20.6
Observer-based	3.57	2.35	5.14	4.7	3.94	32.8
Mean errors	2.93	2.41	3.73	3.75		
% error rate	22.9	19.1	32.5	31.6		

robot-based group was not significant (F(3,39) = 0.651, p=0.587). There was a significant effect of configuration at the observer-based group (F(3,39) = 4.046, p=0.013).

A Tukey test for comparison of means within the observer-based group identified significant differences between configuration B (2.35) with configurations C (5.14) and D (4.7) as shown in Appendix IV.8vi.

Analysis 2. Direction errors

The raw data for direction errors are given in Appendix IV.9i. Again, although there were some zero scores it was decided not to perform a transformation on the data. The Analysis of Variance table is given in Appendix IV.9ii. The only significant result obtained was a main effect between robot configurations; F(3,39) = 6.013, p=0.0018. The mean direction errors in each configuration are shown in Table 6.23. A Tukey test for comparison of means identified significant differences between configurations B (2.07) with C (3.75), p=0.01 and between B (2.07) with D (3.45), p=0.05 (see Appendix IV.9iii).

Analysis 3. Control errors

The raw data for control errors are given in Appendix IV.10i. It was decided that, as the majority of scores were zero errors, it would be inappropriate to perform any statistical analysis on this data.

Analysis 4. Subject response times

The time scores were adjusted to allow for the extra time taken for a selection of a joystick control to produce robot movement (i.e. the time taken for the BBC micro to convert the signal). Over repeated tests, this was calculated to be 0.24 seconds per move. The ammended data for subject response times are given in Appendix IV.11i.

The response times for each subject group using each teach control are shown in Table 6.24. The Analysis of Variance table is given in Appendix IV.11ii. A significant difference in subject response times was observed between the two subject groups, F(1,13) = 11.50, p=0.0048. The robot-based group took, on average, twice as long to make their responses as

Table 6.23 Mean direction errors for each subject group in each robot arm-configuration

Subject group	Robot arm-configuration					
	A	B	C	D	Overall mean	% error rate
Robot-based	1.75	2.0	2.5	2.75	2.25	18.75
Observer-based	3.36	2.14	5.0	4.14	3.66	30.5
Overall mean	2.55	2.07	3.75	3.45		
% error rate	21.2	17.2	31.2	28.6		

Table 6.24 Mean response times (seconds) for each subject group using each teach control

Subject group	Teach control		
	Joystick	Toggle-switch	Mean times
Robot-based	24.19	24.91	24.55
Observer-based	13.9	11.85	12.88
Mean times	19.04	18.38	

the observer-based group (24.5 and 12.8 seconds respectively). However, no significant difference was observed in subject response times using either teach control box; F(1,13) = 0.187, p=0.67.

A significant difference in response times was found between the robot configurations; F(3,39) = 9.301, p=0.0001. The mean response times at each configuration are shown in Table 6.25. A Tukey test for comparison of means identified significant differences between configuration A (16.6) with B (19.08), C (19.43) and D (19.74), p=0.01 (see Appendix IV.11iii).

There was a significant interaction between robot configuration and the subject groups, F(3,39) = 4.162, p=0.0119. This is shown in Figure 6.12. Assessment of the simple main effects, as shown in Appendix IV.11iv, identified significant effects of subject group at all of the configurations; A (F(1,13) = 8.147, p=0.014), B (F(1,13) = 14.376, p=0.002), C (F(1,13) = 13.107, p=0.003) and D (F(1,13) = 8.935, p=0.01). The effect of configuration at the observer-based group was not significant (F(3,39) = 1.124, p=0.351), but was significant at the robot-based group (F(3,39) = 5.927, p=0.002).

A Tukey test for comparison of means at each configuration within the robot-based group identified significant differences between configuration A (21.28) with configurations B (26.11), C (25.23) and D (25.58), p=0.01 (see Appendix IV.11v).

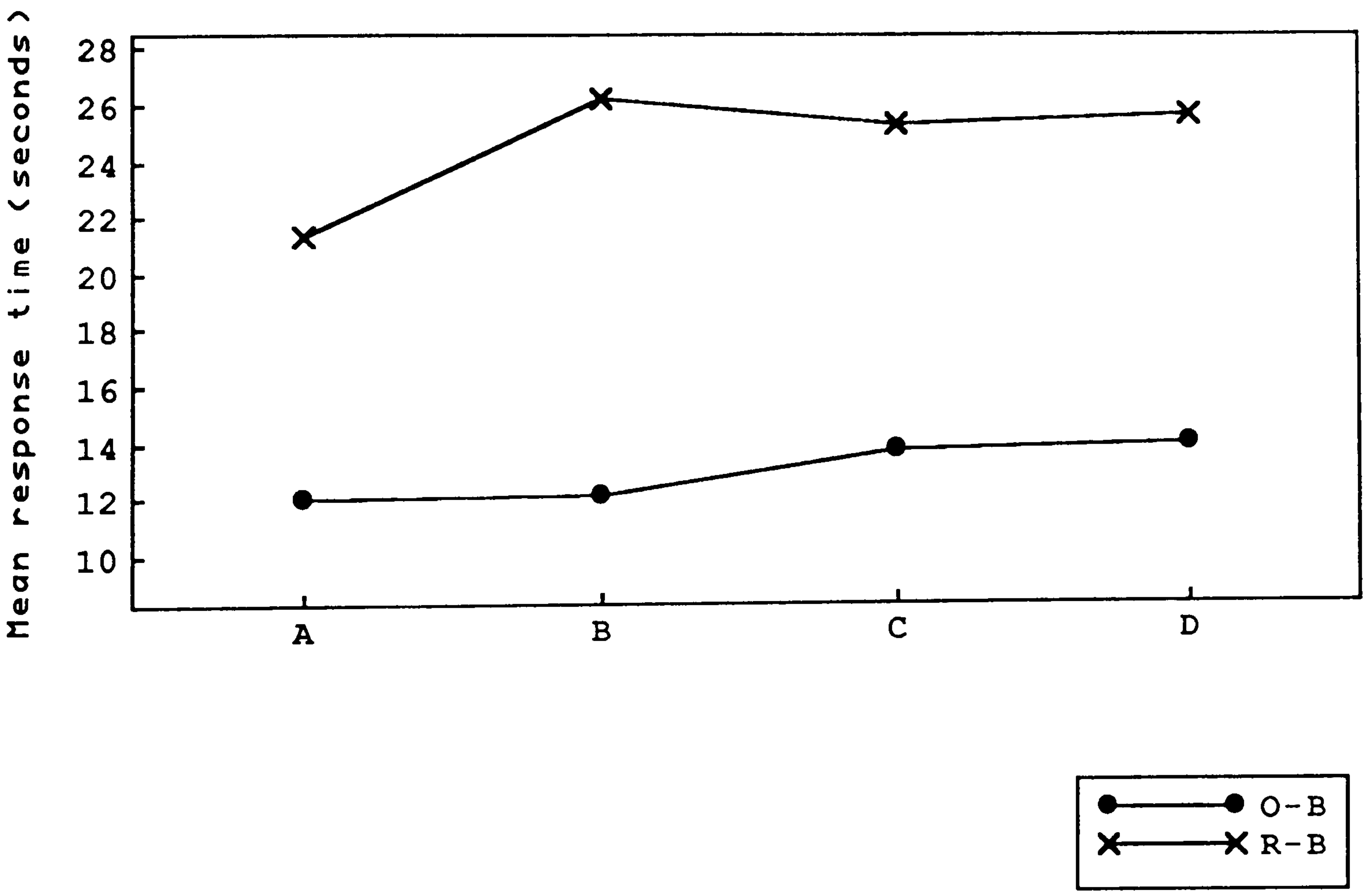
C. Subject preferences

There were some differences in the subject preferences for either teach control but these did not appear to be group-related. In the robot-based group 6/8 subjects preferred the toggle-switches and the remaining two subjects preferred the joystick. In the observer-based group 5/7 subjects preferred the toggle-switches, one subject preferred the joystick and one had no preference. Thus, in total, 11/15 of the subjects preferred the toggle-switch pendant. The main reason given was that it had separate controls for each joint whereas the joystick did not. The three subjects who preferred the joystick, on the other hand, said that this was because they could keep their hand in one position and didn't need to keep looking at the control box to

Table 6.25 Mean response times (seconds) for each subject group in each robot arm-configuration

Subject group	Robot arm-configuration				
	A	B	C	D	Overall mean
Robot-based	21.28	26.11	25.23	25.58	24.55
Observer-based	11.92	12.06	13.63	13.89	12.88
Overall mean	16.6	19.08	19.43	19.74	

Figure 6.12 Mean response times (seconds) for each subject group in each robot arm-configuration



find the control they wanted. One advantage provided by the toggle-switch box for the experimental task was that the direction of control movements for joints 2 and 3 moved in the same way which most of the subjects found easier to use.

The subjects had also been asked to indicate what strategies they had used to help them decide which way to move the robot joints. In the robot-based group, four of the subjects had used some cues on the robot (either the orange wires which provide hydraulic power to the gripper, or logos on the arm) to help them remember when the control directions had reversed (i.e the robot had performed an 'arm-flip' movement into a new configuration). The remaining four subjects in the robot-based group did not use such cues to help them recognise the current arm-configuration but stated that they had memorised the control-motion relationship in the 'normal' configuration (position A) and related each new configuration to this.

In the observer-based group, four of these subjects had also used cues on the robot (the orange wires or logos) to help them remember which way to move joints 2 and 3. These subjects said that they had realised that the joint directions were continuously changing but did not quite comprehend why. However, they found that the cues provided them with a simple strategy which seemed to work; when the orange wires were above the joint the '+ve' control would move the joint upward, and when the orange wires were below the joint then the '-ve' control would move the joint upward. The remaining three subjects in the observer-based group said that they had not used any cues on the robot at all. Interestingly, these three subjects (5, 9 and 12) has a generally higher error rate than any of the other subjects (see raw data table given in Appendix IV.8i).

Finally, the subjects had been asked to suggest how the control-motion arrangement could have been altered to make the task easier. Five of the subjects would have preferred the control for joint 1 to be rotary (i.e. like the top of the joystick) to correspond with joint 1 movement. Seven subjects suggested that the toggle-switches for joint 2 and 3 should be moved forward/back rather than right/left. Two subjects suggested a small model of the robot arm so that you controlled the actual part of the robot that you wanted to move. Four subjects suggested colour-coding the robot arm amd labelling the control directions by colours to remove the confusion of reversed directions. Two subjects suggested some kind of electronic display on the teach pendant to indicate when the arm-configuration had changed. Five subjects said that they felt something else might have been easier but couldn't offer any solutions.

6.3.1.4 Discussion

The experiment examined the effect that a robot configuration change has on the use of teach pendant controls when programming in Joint mode. On the basis of the previous experimental findings (in stages 1 and 2), the subjects were classified before performing the experimental task acording to their perceptual frame of reference (i.e. robot-based or observer-based). It was expected that each group would perform differently and that, in particular, the observer-based group would make more errors than the robot-based group.

The results showed that, for total error scores, the observer-based group made considerably more errors than the robot-based group (50% more) although this was not statistically significant. Examination of the raw data (given in Appendix IV.8i) indicated that most of these errors had been made by three of the observer-based subjects who had made substantially more errors than all of the other subjects in both groups. Interestingly, these three subjects had not used cues on the robot to help them remember which direction to move the controls whereas the other four subjects in the observer-based group had done so. This suggests that, given feedback from actual robot movement, the use of cues on the robot arm facilitated correct identification of directional control movements for subjects who had been classed as using an observer-based frame of reference. Thus, they had realised that a movement of the joint 'upward' was not always achieved by moving the control in the '+ve' direction, and developed a simple strategy (e.g. which side of the joint the hydraulic wires were on) to help them decide whether the 'upward' movement would be produced by the '+ve' or '-ve' control. It could be argued that these four subjects were not using their 'observer-based' frame of reference to make their control decisions but were using an 'object-based' frame of reference (i.e. towards or away from the wires, etc) instead, with the result that their performance was more like that expected from the robot-based subjects.

It is also possible that, given feedback from robot movement, the subjects changed their perceptual frame of reference from observer-based to robot-based. The results of the pre-experiment and post-experiment classification tests, where four of the observer-based group were classed as robot-based in the latter test, suggest that this may be so. However, it is just as likely that, in the post-experiment test, these subjects may have used the 'object-based' strategy, developed during the experiment, to identify the correct movement.

As expected, there was a significant difference in total error scores made at different configurations with 50% more errors being made in the LEFTY arm-configuration (C and D) than in the RIGHTY arm-configuration (A and B). It was expected, however, that this effect would be observed for the observer-based group only as the robot-based group should not be confused by arm-configuration changes. It was therefore appropriate to investigate the group-configuration interaction even though it had not been found to be significant (p=0.0599). This analysis did identify that there were no significant differences within the robot-based group and that the observer-based group had made significantly more errors in the LEFTY arm-configuration (C and D) than in the RIGHTY arm-configuration (B only). Examination of the raw data (see Appendix IV.8i) suggests that the effect was mostly produced by the three observer-based subjects who had made higher errors than all of the other subjects and that the non-significant interaction was the result of the reduced effect produced by the other four subjects in the observer-based group.

Examination of the data for type of errors made revealed that most of the errors had been direction rather than control errors. Thus, in general, the subjects had not found difficulty in finding the correct control for each joint but had made errors in moving the control in the correct direction. Similar results for the analysis of total errors were obtained in the analysis of direction errors although the difference between arm-configurations was less clear-cut. Significantly more errors had been made in the LEFTY arm-configuration (C and D) than in configuration B.

There was a significant difference between the subject groups in the analysis of response times. Subjects classed as using a robot-based frame of reference took twice as long as those classed as using an observer-based frame of reference to make their responses (24.5 secs compared to 12.8 secs). A possible explanation of this may be that, for each configuration, the robot-based subjects needed to 'mentally transform' the appearance of the robot to match their reference point (position A), which may require extra 'thinking' time. In the post-experiment interviews four of the robot-based subjects stated that their strategy was to memorise the control-motion relationship for the training position (A) and then related each new configuration to configuration A before they could work out which direction to move the control. Two of these subjects had used a rotation terminology for describing direction of movement and these subjects said that they 'imagined' a 'clockface' on the front of the robot joint as it appeared in configuration A . When the arm-configuration was reversed, they had to reverse the 'mental image' of the clockface to determine which direction the joint should be moved in.

The significant difference in response times observed at each configuration was found to be explained by the robot-based group in the simple effects analysis of the group-configuration interaction. Response times were significantly faster in configuration A than in configurations B, C and D which does support the above hypothesis. However, this does not explain why the mean response time in configuration A (training position) was significantly higher for the robot-based group than the observer-based group. It is suggested that the observer-based subjects did not spend as much time 'thinking' about their responses but made simple decisions about whether the joint should be moved up/down or towards/away from their reference cues, whereas the robot-based subjects thought about the control-motion relationship even when the robot was in the training position.

There were no statistically significant differences observed in any of the measures between the two teach boxes, although 30% more errors had been made using the joystick. However, there was a strong preference among the subjects (73%) for the toggle-switch box. These subjects had preferred the separate controls for each joint provided by the teach box and found that it was more confusing to remember which way to move the joystick controls. The subjects who had preferred the joystick control, on the other hand, had liked it because they found it easy to distinguish between the three controls without looking at the control box. The main criticism from most of the subjects concerning either teach control was that the movement of the controls did not match the corresponding movement of the robot joint. Thus, they would have preferred that joint 1 was operated by a rotary control and that joints 2 and 3 should be moved forward/back rather than left/right. However, some of the subjects did recognise that, due to the direction reversals produced by arm-configuration changes, this arrangement may cause further confusion.

6.3.2 Experiment 6: Control performance in world mode.

6.3.2.1 Procedure

The subject was positioned at the front of the robot with the robot gripper nearest the subject and joints 2 and 3 at 90° angles (as shown in Figure 6.13). The subject was shown how the robot could be moved along each of the three main axes (X, Y and Z) in each of two directions (+/-). In the same way as in experiment 4 (the procedure for which was described in section 6.2.1), the axes were identified verbally, e.g. "This is movement along the X axis", but no verbal description was given to directional movements.

A. Subject classification

In this experiment only one method of subject classification was used; subjects' descriptions of the movements they saw (i.e. the World mode equivalent of classification method 1 described in section 6.3.1.1). It was not appropriate to perform a World mode equivalent of classification method 2 as arm-configuration changes do not affect the direction of movements made in World mode.

With the subject still positioned at the front of the robot, they were then shown each individual movement again but this time they were asked to describe each move (both the axis of movement and the direction of movement). In the same way as in the Joint mode experiment (described in section 6.3.1.1), the subjects were told that they had completed a practice of the first part of the task in order to familiarise them with the task. In fact, in order to prevent the subjects choosing different perceptual reference points as in experiment 4 (discussed in section 6.2.4.2), the practice task was used to establish the subjects' perceptual reference point whilst they were facing the robot from the front orientation.

The subject was then positioned at either the front, back or side of the robot (they were told what each position was). Again, they were shown each robot move (in a different order to previously) and asked to describe them. They were then moved to another position, where the task was repeated and again from the final position. From these descriptions the subjects were classified according to the pattern of responses they gave. Using the same method as in the Joint mode experiment, if the subject's description of each actual movement when viewed at different human-robot orientations was consistent with their description of it during the practice task, they were classified as using a robot-based frame of reference. If, however, their descriptions were inconsistent, they were classified as using an observer-based frame of reference.

The classification of each subject is presented in the results section (6.3.2.3).

B. Control performance

The subject was positioned at the front of the robot and was given a teach control box (either the joystick or toggle-switch box). As in the Joint mode experiment, half of the subjects used the joystick first and the other half used the toggle-switch box first. The subjects were told that the controls on the teach box could be used to control the robot axes in the same way that they had just seen them move. They were given time to practise with the controls and familiarise themselves with the control-motion relationship. This was unlimited time, lasting until the subject stated that they understood the control-motion relationship; in general this took no more than 2 minutes.

For the experimental task the subject was positioned at either the front, back or side of the robot. A 3-D maze (previously shown in Figure 5.17 and described in section 5.3.7) was located directly in front of them and the robot arm was positioned above the start of the maze. A pencil had been placed in the robot gripper and the tip of the pencil was placed just above the maze. The subject was told that their task was to guide the pencil along the maze using the X, Y and Z controls on the teach box. They were told that their errors would be recorded and that they would be timed from the beginning to the end of the maze. They were also told that they must keep the control box at the same orientation to themselves at all times (e.g. with the cable nearest to them). The experimental task was repeated at each subject-robot position with the same control box. The entire experimental task was repeated one week later with the other control box.

6.3.2.2 Design

Twelve male undergraduate students, aged 18 - 25, took part in the experiment . This experiment also consisted of two 1-hour sessions and the subjects were paid £8 on completion of the second session.

Six treatment conditions were considered in the experiment being combinations of teach control and subject position;

a) teach control (joystick or toggle-switch)
b) position of subject (front, back or side)

The subjects were classified into either of two groups according to their perceptual frame of reference determined from their descriptions of robot movement (observer-based or robot-based). All the subjects performed the task in all six treatment conditions.

For analysis of control performance a three-factor (2 x 2 x 3) ANOVA with repeated measures design was applied.

The factors were defined by;

a) subject group (robot-based or observer-based)
b) teach control (joystick and toggle)

c) subject orientation (front, back and side)

Subjects' performance was evaluated by;

i) correct or incorrect axis movement where an incorrect response was defined as being either;

a) direction error = moving the correct axis but in the wrong direction, or

b) control error = moving the wrong axis (in any direction)

ii) task completion time (i.e. the duration between the first movement and reaching the end of the maze)

Thus, there were four analyses performed on the results;

Analysis 1. Total errors

Analysis 2. Direction errors

Analysis 3. Control errors

Analysis 4. Task completion time

The maze (previously shown in Figure 5.17) consisted of 28 discrete movements; 10 along the X axis (5+ve, 5-ve), 10 along the Y axis (5+ve, 5-ve) and 8 along the Z axis (4+ve, 4-ve). The maze path was randomly set out within the constraints of the four sides of the box. The length of each X and Y movement varied between 4 cm and 12 cm (again due to the constraints of free space within the box) but the length of each Y axis movement was consistently 6 cm (the length of the pencil placed in the robot gripper). By repositioning the maze relative to the subject, the presentation order of the X and Y axes movements were varied (i.e. the first movement could be X+ve, X-ve, Y+ve or Y-ve depending upon which edge of the box was facing the subject). Further variation was achieved by alternating the direction of the maze path (i.e. which end of the maze was used as the start). Thus, there were eight alternative path sequences available and these were presented such that no subject repeated the same sequence twice.

On the basis of the findings of experiment 4 (discussed in section 6.2.4.2) it was expected that the subjects classed as observer-based would make more errors than those classed as robot-based. Moreover, they would produce direction errors from the back orientation and control errors from the side orientation.

6.3.2.3 Results

A. Subject classification

The results of subject classification are shown in Table 6.26. Two types of terminology were used for describing direction of axis movement; either as 'positive' or 'negative' for each axis, or as 'left/right', 'back/forward' or 'up/down' in relation to the training position (front orientation). Of the six subjects who used the '+ve/-ve' terminology, three had described axis movements consistently when viewed from different orientations and were therefore classed as using a robot-based frame of reference (subjects 1, 5 and 12). The remaining three subjects had not described the axes movements consistently when viewed from different orientations and were therefore classed as using an observer-based frame of reference (subjects 4, 8 and 9). Of the six subjects who had described the axes movements in relation to the front orientation, two had described these consistently form other orientations and were therefore classed as using a robot-based frame of reference (subjects 2 and 7). The remaining four subjects had described the axes movements relative to the current orientation from which they viewed the robot and were therefore classed as using an observer-based frame of reference.

It can be seen that after the pre-experiment test five subjects were classed as robot-based and seven were classed as observer-based. Table 6.26 also shows the results of the post-experiment test performed after the second session of the experimental task had been completed. It can be seen that all but three of the subjects were classed in the same way as in the first test. The three subjects that had changed had all been classed as observer-based in the first test but robot-based in the second test (subjects 6, 9 and 11).

B. Control performance

Analysis 1. Total Error scores

The raw data for total error scores are given in Appendix IV.12i. Due to the frequency of zero scores it was decided that transformation of the data (natural logarithm (x+1)) would be appropriate. The ANOVA table is shown in Appendix IV.12ii. The only significant result

Table 6.26 Subject classification for experiment 6 before and after performing the experimental task

Subject	Terminology			Frame of reference		changes
	X	Y	Z	Pre-experiment	Post-experiment	
1	+/-	+/-	+/-	R-B	R-B	
2	L/R	F/B	U/D	R-B	R-B	
3	L/R	A/T	U/D	O-B	O-B	
4	+/-	+/-	+/-	O-B	O-B	
5	+/-	+/-	+/-	R-B	R-B	
6	L/R	F/B	U/D	O-B	R-B	O-B-->R-B
7	L/R	F/B	U/D	R-B	R-B	
8	+/-	+/-	+/-	O-B	O-B	
9	+/-	+/-	+/-	O-B	R-B	O-B-->R-B
10	L/R	F/B	U/D	O-B	O-B	
11	L/R	F/B	U/D	O-B	R-B	O-B-->R-B
12	+/-	+/-	+/-	R-B	R-B	

+/- = positive/negative
L/R = left/right
F/B = forward/back
A/T = away/towards
U/D = up/down

R-B = robot-based
O-B = observer-based

obtained was a main effect between the subject-robot orientations F(2,20) = 12.628, p=0.0003. The mean errors are shown in Table 6.27a and the mean errors of the transformed data are shown in Table 6.27b. A Tukey test for comparison of the log means identified significant differences between the front orientation (0.59) with the back (1.27) and side (1.29) orientations, p=0.01 (see Appendix IV.12iii).

Analysis 2. Direction errors

The raw data for direction errors are given in Appendix IV.13i. Again, the analysis was performed on transformed data (natural logarithm (x+1)). The Analysis of Variance table is given in Appendix IV.13ii. Again, the only significant result obtained was a main effect between the orientations; F(2,20)=15.5, p=0.0001. The mean direction errors are shown in Table 6.28a and the mean errors of the transformed data are shown in Table 6.28b. A Tukey test for comparison of the log means identified significant differences between the front orientation (0.41) with the back (1.18) and side (1.12) orientations, p=0.01 (see Appendix IV.13iii).

Analysis 3. Control errors

The raw data for control errors are given in Appendix IV.14i. It was decided that, as the majority of scores were zero errors, it would be inappropriate to perform any statistical analysis on this data.

Analysis 4. Task completion time

As in the Joint mode experiment, the time scores were adjusted to allow for the extra time taken for a selection of a joystick control to produce robot movement (i.e. the time taken for the BBC micro to convert the signal) Over repeated tests, this was calculated to be 0.24 seconds per move. As the task completion time included 28 discrete movements, 6.7 seconds (0.24 x 28) were deducted from each of the joystick time scores.

Table 6.27a Mean errors for each subject group at each human-robot orientation

Subject group	Human-robot orientation			Overall mean	% error rate
	Front	Back	Side		
Robot-based	0.90	2.80	2.80	2.16	7.7
Observer-based	1.35	4.21	5.14	3.57	12.8
Overall mean	1.12	3.50	3.97		
% error rate	4.0	12.5	14.2		

Table 6.27b Log mean errors for each subject group at each human-robot orientation (transformed data)

Subject group	Human-robot orientation			Overall mean
	Front	Back	Side	
Robot-based	0.48	1.01	1.09	0.86
Observer-based	0.69	1.53	1.50	1.24
Overall mean	0.59	1.27	1.29	

Table 6.28a Mean direction errors for each subject group at each human-robot orientation

Subject group	Human-robot orientation			Overall mean	% error rate
	Front	Back	Side		
Robot-based	0.60	2.30	2.40	1.76	6.3
Observer-based	1.00	3.78	3.85	2.88	10.3
Overall mean	0.80	3.04	3.12		
% error rate	2.8	10.8	11.1		

Table 6.28b Log mean direction errors for each subject group at each human-robot orientation (transformed data)

Subject group	Human-robot orientation			Overall log mean
	Front	Back	Side	
Robot-based	0.32	0.91	1.00	0.75
Observer-based	0.50	1.44	1.23	1.06
Overall log mean	0.41	1.18	1.12	

The ammended data for task completion times are given in Appendix IV.15i. The Analysis of Variance table is given in Appendix IV.15ii. The mean task completion times using each teach control are shown in Table 6.29. No significant main effect was found between the two subject groups; F(1,10) = 0.032, p=0.86. A significant main effect was observed between each teach control; F(1,10) = 5.513, p=0.0408, with the task taking longer using the joystick than the toggle-switch pendant (145.1 and 137.6 seconds respectively).

A significant main effect was observed between the subject-robot positions; F(2,20)=7.033, p=0.0049. This is shown in Table 6.30. A Tukey test for comparison between means identified significant differences between the front orientation (135.04) with the back (144.68) and side (144.51) orientations, p=0.05 (see Appendix IV.15iii).

C. Subject preferences

There were differences in the subject preferences for either teach control but most of the subjects (9/12) preferred the toggle-switches to the joystick. In the robot-based group 3/5 subjects preferred the toggle-switches and the remaining two preferred the joystick. In the observer-based group 6/7 subjects preferred the toggle-switches and the remaining one preferred the joystick. Those who preferred the toggle-switches claimed that the joystick was more confusing and that it was too easy to move the wrong control by mistake. Those who preferred the joystick favoured the compatibility of the X and Y axes controls with their corresponding robot movements and suggested that the toggle-switches would be better if the Y axis control was operated forward/back rather than left/right.

Two subjects suggested that the Y axis control would be easier to use if the +/- directions were reversed. Two subjects suggested that the Z axis control should operate vertically up/down. One subject suggested that the joystick control would be the easiest to use if the computer program changed the function of the controls in accordance with the operator's orientation to the robot (i.e. the control-motion relationship would be compatible from all orientations).

Table 6.29 Mean task completion times (seconds) for each subject group using each teach control

Subject group	Teach control		
	Joystick	Toggle-switch	mean time
Robot-based	143.36	138.6	140.98
Observer-based	146.96	136.7	141.84
Mean time	145.16	137.65	

Table 6.30 Mean task completion times (seconds) for each subject group at each human-robot orientation

Subject group	Human-robot orientation			
	Front	Back	Side	mean time
Robot-based	134.65	141.35	146.95	140.98
Observer-based	135.44	148.01	142.08	141.84
mean time	135.04	144.68	144.51	

Many of the subjects said that they had found that they were quickly able to adjust to the direction reversals at each configuration and that the speed of robot movement was slow enough for them to plan the next movement before they reached it.

6.3.2.4 Discussion

This experiment examined the effect that changes in human-robot orientation have on the use of teach pendant controls when programming in the World mode. On the basis of the previous experimental findings (in stages 1 and 2), the subjects were classified before performing the experimental task according to their perceptual frame of reference (i.e. robot-based or observer-based). It was expected that the subjects classed as observer-based would make more errors than those classed as robot-based and that they would make directions errors when the task was performed at the back orientation and control errors when the task was performed at the side orientation.

The results showed that, for total error scores, the observer-based group did make more errors than the robot-based group (60% more) although this was not statistically significant. Probably the most important reason for this was the extremely low incidence of error scores made by both subject groups; the robot-based group had made on average only 2.2 errors (8%) and the observer-based group had made on average 3.6 errors (13%). Thus, given the variation of performance errors within each subject group (see raw data in Appendix IV.12i), they could not be said to be clearly distinguishable in their performance patterns.

These generally low error rates, by comparison to those observed in the Joint mode experiment (see section 6.3.1.3), possibly reflect the less complicated nature of the World mode experimental task. For example, World mode movements are not subject to direction reversals under any circumstances since they are fixed within the world coordinate reference frame. Those subjects who might expect World mode directions to alter according to their own orientation to the robot (i.e. observer-based subjects) may realise that this wasn't so when feedback form observation of robot movement was provided. Indeed, of the seven subjects classified as observer-based in the pre-experiment test, three were classed as robot-based in the post-experiment test indicating that this may have been the case. In addition,because it had been impractical to continuously move the subjects to different human-robot orientations during the experiment (thereby replicating the Joint mode experiment), the entire task of 28 movements was completed before the subject was moved to a different orientation. Thus, within the first few movements the subjects were able to learn the control-motion relationship for their current orientation and therefore made virtually no errors during the latter part of the experimental task. Furthermore, many of the subjects commented that the speed of robot motion was slow enough to allow them 'thinking time' before the end of each path was reached. Thus, they were able to 'plan' what the next movement would be and how they should move the controls to achieve it.

As expected, there was a significant difference in total error scores made at different human-robot orientations with more errors being made at the back and side orientations than the front. Unexpectedly, however, the majority of these errors were direction errors with virtually the same amount being made at the side orientation as the back orientation.

No significant difference was observed between each subject group in their task completion times. A possible explanation of this may be that the subjects had all been restricted by the imposed speed of robot motion which provided sufficient time for them to plan ahead their required control actions.

There was a significant difference observed between each teach control in task completion times, with the task taking 5% longer using the joystick than the toggle-switch controls. This may have been because the joystick control presented the subjects with a more complicated task due to its direct control-motion compatibility when controlling the robot from the front orientation and relative incompatibility at the other orientations. Although this did not result in more errors being made using the joystick, 2/3 of the subjects said that they had to concentrate harder when using the joystick control and consequently expressed a preference for the toggle-switch design.

The significant difference in task completion times observed at each orientation corresponded with the error performance at each orientation. Thus, the task took significantly longer to complete at the back and side orientations than the front orientation. The extra time was most likely due to correcting for the direction errors made at these orientations.

CHAPTER 7 - DISCUSSION

CHAPTER 7 - DISCUSSION

7.0 Introduction

The work presented in this thesis has identified and examined human factors relating to the reliability of performance in industrial robot motion control. These factors can be divided broadly into two main types; robot system factors and human cognitive factors. Whilst the impetus of this research was in consideration of the feasibility of standardisation in robot teach pendant design and the subsequent question of what the most suitable design(s) would be, theoretical analysis of the motion control task indicated that other robot system factors might add to the complexity of the control task; principally these factors were thought to be control-motion compatibility and conditions producing motion reversals. Moreover, it was anticipated that (operator) cognitive processing of these factors might influence performance reliability.

These robot system factors were represented in a framework depicting the motion control process and the relationships between the two types of factors (illustrated in Figure 4.17 and described in section 4.5). This framework formed the basis of the main experimental programme of this research, which examined three different circumstances of control-motion compatibility and motion reversal conditions: perception of robot motion under different conditions of motion reversal; perception of control-motion compatibility; and control performance reliability with motion feedback. The results of the individual experiments have already been discussed in chapter 6 and therefore will not be discussed at length in this chapter. Here the findings of the experimental work will be discussed within the context of information processing and with regard to cognitive issues in robot motion control.

The discussion chapter is divided into five sections. The first section will discuss the process of robot motion control, the development of the framework representing this process, and its revision in the light of the experimental findings. The experimental methods used and their advantages and limitations will be discussed in the second section. In the next two sections the individual factors within the framework will be discussed, first those factors relating to human information processing and then those relating to the robot system . In the final section other factors relating to the motion control task and the issue of control design standardisation will be discussed.

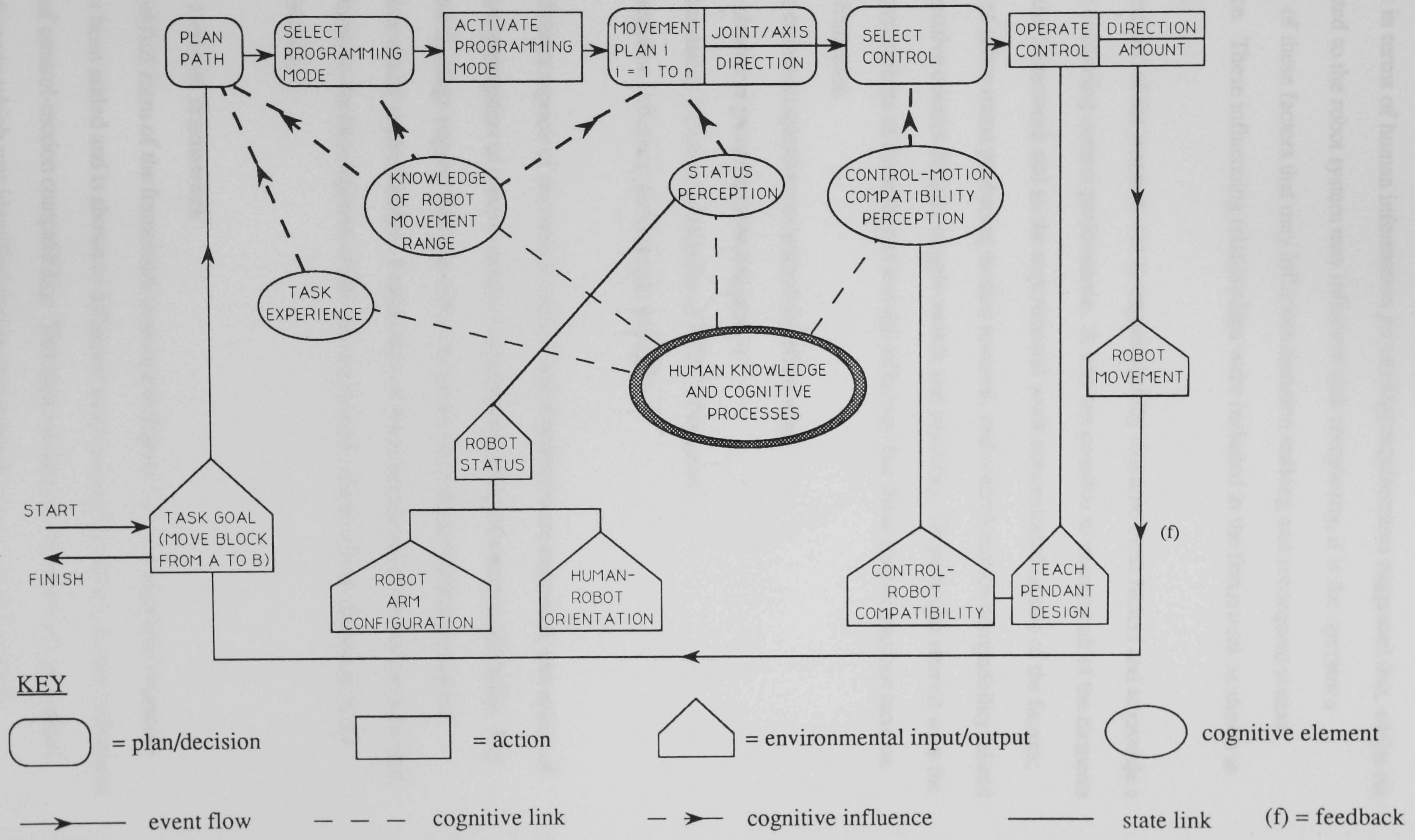
7.1 The robot motion control process

7.1.1 Development of the framework

The first aim of the present research work was to fully explore the task of robot motion control using a teach pendant. This was initially achieved using a task analysis method carried out at some industrial sites (as described in section 4.1). Several different robot systems were examined and it was observed that the systems differed in the way that program input was achieved but that the basic functions of the motion controls were common to each system. Excepting the need to supply power to the robot arm, four factors were identified in the control of robot motion; selection of programming mode (joint, world or tool), the degree of freedom to be moved (the joint or axis), the direction and the speed of the movement. Although the task analysis approach was limited in that, in itself, it was not an appropriate tool for assessment of task difficulty, as a description of the task it formed the basis of the framework depicting the motion control process. Initially the framework simply represented the sequence of actions required to achieve robot movement together with the decisions associated with each action (see Figure 4.5, described in section 4.2). No assumptions were made about the sequence of decision-making nor, at this stage, the factors influencing those decisions.

The second aim of the research was to identify these influencing factors. Three factors were defined representing human characteristics (e.g. the operator's knowledge and experience), situational conditions (e.g. motion reversals caused by changes in robot status) and control design factors (e.g. teach pendant design and control-motion compatibility), described in section 4.4. These factors were added to the framework according to the theoretically assumed relationships between them and the stages of the control process. The framework, previously shown in Figure 4.17, is re-presented in Figure 7.1. Consideration of

Figure 7.1 Framework of the robot motion control process



the process in terms of human information processing requirements suggested that, whilst the factors related to the robot system may influence task complexity, it is the operator's *perception* of these factors that may influence decision-making and subsequent control performance. These influencing relationships were included in the framework as shown in Figure 7.1.

The third aim of the research was to experimentally examine these factors and to provide a method for evaluating control performance. It was not possible to examine all of the elements defined in the framework and so the experimental work concentrated on two of the factors; conditions of robot status producing motion reversal, and control-motion compatibility related to two alternative control designs (toggle-switch and joystick). Of particular interest were the operator's perceptions of these factors and the influence that these may or may not have on control performance.

The experimental questions examined therefore were;

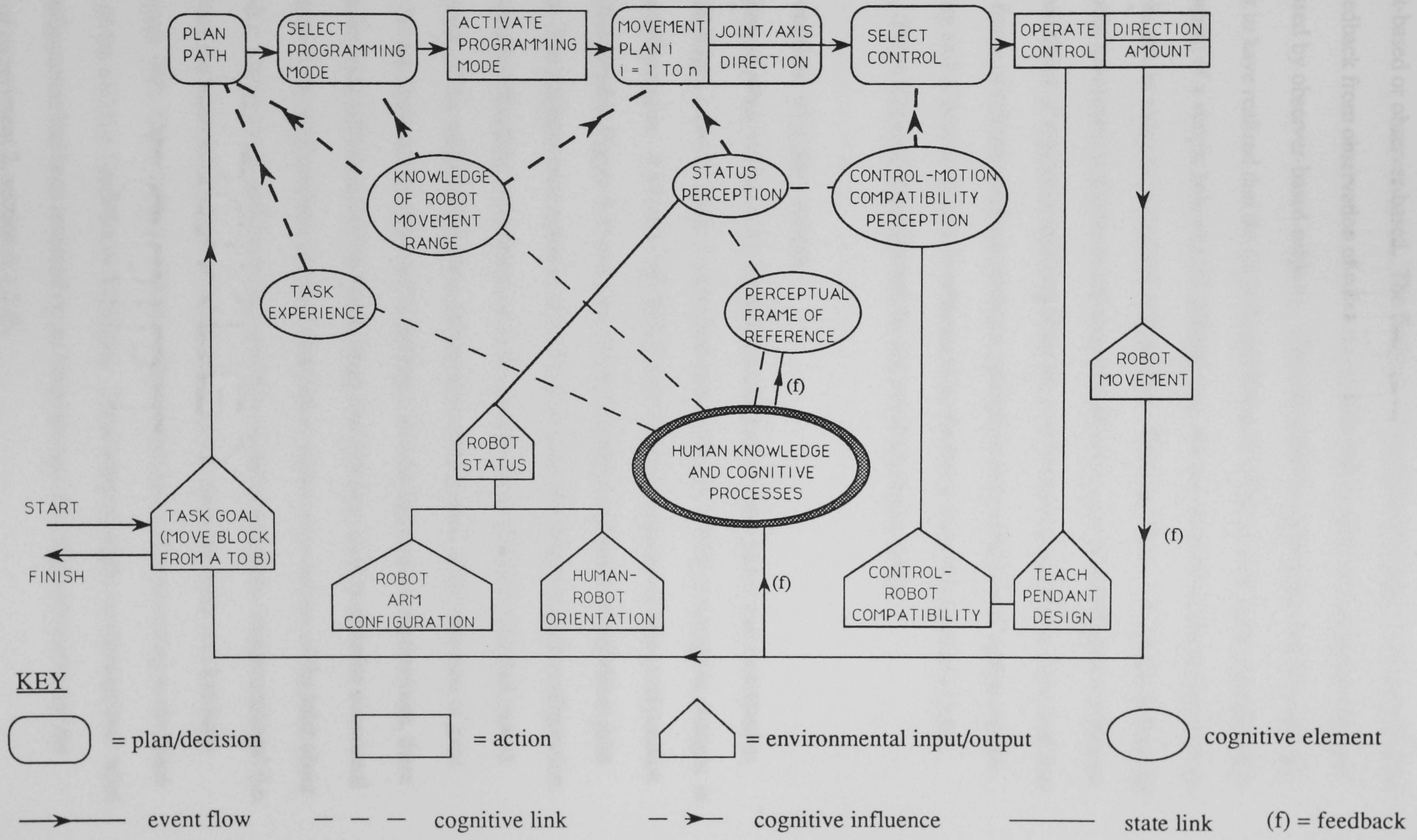
1. How do observers perceive robot movement?
2. Does robot status influence perception of robot movement?
3. Does perception influence performance reliability?

Three distinct aspects of the motion control task therefore were examined; perception of robot motion, perception of control-motion compatibility, and performance reliability. The experimental findings suggest that task difficulty arises more from operator perceptual problems than actual control design. Explanation of these perceptual problems has provided additional input to the development of the task framework which will be discussed in the following section.

7.1.2 A revised framework

The modified form of the framework is shown in Figure 7.2. An additional cognitive element has been added and is shown to influence status perception which, in turn, influences perception of control-motion compatibility. This new element is the observer's perceptual frame of reference which was identified during experimental stages 1 and 2 as being

Figure 7.2 Modified framework of the robot motion control process



either robot-based or observer-based. The findings of experimental stage 3 indicated that the effect of feedback from observation of robot movement was to alter the perceptual frame of reference used by observer-based subjects. This was either by perception modification (i.e. they appear to have realised that the robot-based frame of reference was more appropriate) or by development of a simple behavioural strategy (e.g. the use of environmental cues such as wires, labels, etc. to assist in perceptual orientation). Thus, in Figure 7.2, feedback from the resultant robot movement is shown to influence the observer's perceptual frame of reference.

The main thrust of argument resulting from the experimental programme, then, is of how perceptual frame of reference influences status perception and perception of control-motion compatibility and of how it, in turn, is influenced by feedback from observation of robot movement. These three relationships will be discussed separately below.

7.1.3 Perception of robot status

Perception of robot motion under different conditions of robot status was examined in experimental stages 1 and 2. Stage 1 examined naive subjects' ability to recognise changes in robot arm-configuration. A PUMA 560 (Mk I) robot was put into one of four configuration positions (illustrated in Figure 5.9) and then moved through a sequence of individual joint movements. The subjects were asked to describe each joint movement in each configuration.

No particular difficulties were observed in the identification of which joint had moved. However, some of the subjects had given inconsistent descriptions of the direction of joint movement for the same moves observed in different arm-configurations. Furthermore, these inconsistencies were influenced by the terminology that had been used to describe directional motion. Some of the subjects had described directional motion as a rotation of the joint about its linkage (i.e. clockwise or anticlockwise) and these subjects had made ‘misperceptions’ (i.e. they had given inconsistent descriptions of the same move) when the robot arm had been rotated through 180°. Other subjects had described directional motion according to the linear translation of the tool (i.e. up/down or left/right). These subjects made ‘misperceptions’ when the arm-configuration had been reversed by an ‘over-the-top’ arm-flip movement (see the discussion of experiment 2, section 6.1.2.4).

Experimental stage 2 examined naive subjects' perception of individual robot movements when viewed from different human-robot orientations (front, back, left and right). Two experiments were carried out during this stage examining movements in joint and world modes of programming. As in the previous experiment it was found that the subjects used different terminologies for describing the direction of robot movement. In the joint programming mode, both the rotation and linear movement terminologies were used and it was observed that these terminologies produced different 'misperceptions' under different conditions of human-robot orientation. When the rotation terminology was used different descriptions were given from the front and right orientations compared to the same movement when viewed from the left and back orientations. With the linear movement terminology, a different description was given at each orientation (previously shown in Table 6.9). In the world programming mode, only the linear movement terminology was used and only movements along the X and Y axes produced inconsistencies in direction description. For these a different description of a movement was given from each human-robot orientation (previously shown in Table 6.15).

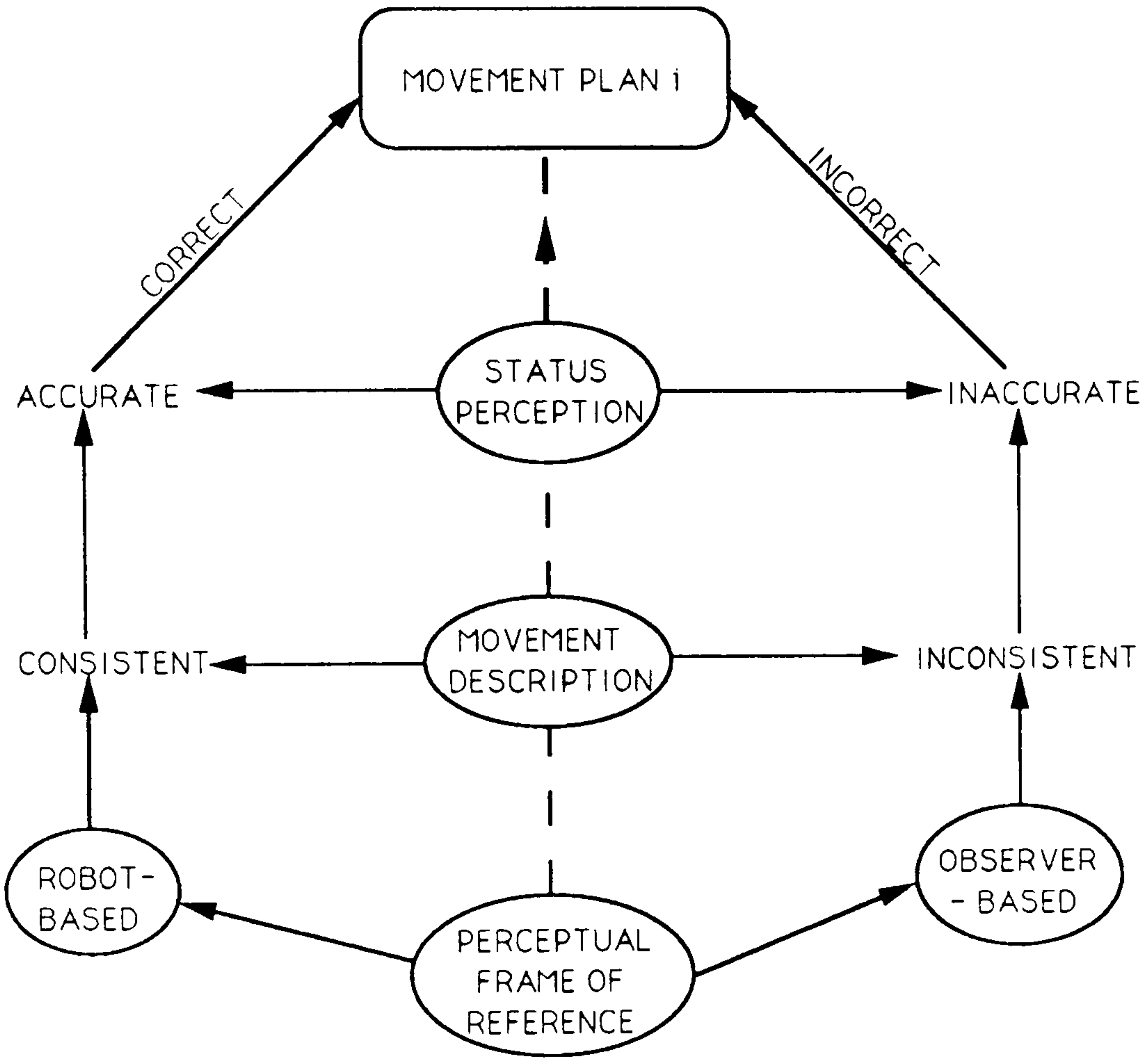
Inconsistencies in direction-of-movement description identified in these experiments were shown by only a few of the subjects in each experiment. The remaining subjects had given consistent descriptions of individual robot movements regardless of the conditions of robot status in which they were presented or the terminology used for description, see results described in sections 6.2.3.1, 6.2.4.1, and 6.2.5. On the basis of these findings it was concluded that the subjects had used different 'frames of reference' for their perception of robot motion. The subjects who had given inconsistent descriptions were defined as using an 'observer-based' perceptual frame of reference because they perceived each motion in accordance with how it appeared to *themselves* at the time. The subjects who gave consistent descriptions were defined as using a 'robot-based' perceptual frame of reference because they perceived each motion in accordance with a reference frame fixed on the robot itself which consequently moved with the robot.

As an example, in the world mode experiment (experiment 4), the same set of individual axis movements were observed from each of the four human-robot orientations. In chapter 4 (section 4.4.2.1) it was shown that a positive movement along the X axis moved the Tool

Centre Point (TCP) in a straight line to the left of the observer viewing the robot from the front orientation. At other orientations, however, the same movement would move the TCP in different directions relative to the observer (e.g. when viewed from the back orientation the TCP would move to the right of the observer as shown in Figure 4.10). The distinction between subjects using an 'observer-based' or 'robot-based' perceptual frame of reference was made on the basis of their descriptions of individual movements when viewed in these conditions of direction reversal. In the case of the above example, four of the twelve subjects who participated in the experiment described this movement differently from each orientation in accordance with the direction that the TCP moved relative to themselves (i.e. "left", "away", "towards" and "right" when viewed from the front, left, right and back orientations respectively as shown in Table 6.15). These subjects were described as using an 'observer-based' perceptual frame of reference. The remaining eight subjects all gave consistent descriptions of the movement at each orientation from which it was viewed (see Table 6.15), in obvious contradiction to the appearance of the movement from three orientations. These subjects were thus described as using a 'robot-based' perceptual frame of reference.

Figure 7.3 illustrates the potential influence of perceptual frame of reference on movement planning. In experimental stages 1 and 2, the observers' perceptual frame of reference was found to influence their description of robot movement and consequently their status perception. It will be remembered that status perception refers to the observer's ability to recognise and identify the current robot status (that is, the combined conditions of robot arm-configuration and human-robot orientation). For example, a 'robot-based' perceptual frame of reference produces consistent descriptions of individual robot movements when viewed in alternative status conditions. It is suggested that this consistency reflects the observer's *accurate* perception of robot status. Thus, the subjects who used this perceptual frame of reference did so because they recognised the conditions of status change; that is that *they* had moved in relation to the robot and that consequently they should describe the movement according to how it *would appear* when viewed from their initial orientation (the training orientation).

Figure 7.3 Influence of perceptual frame of reference on movement planning



The subjects who used an 'observer-based' perceptual frame of reference, on the other hand, did not recognise that the change in status conditions would alter their relationship to the robot in this way and consequently they did not compensate for this in their description of robot movement. These subjects gave inconsistent movement descriptions which were assumed to reflect inaccuracy in status perception. It is anticipated that accurate status perception will allow correct movement planning, whereas inaccurate status perception will lead to incorrect planning under conditions of motion reversal.

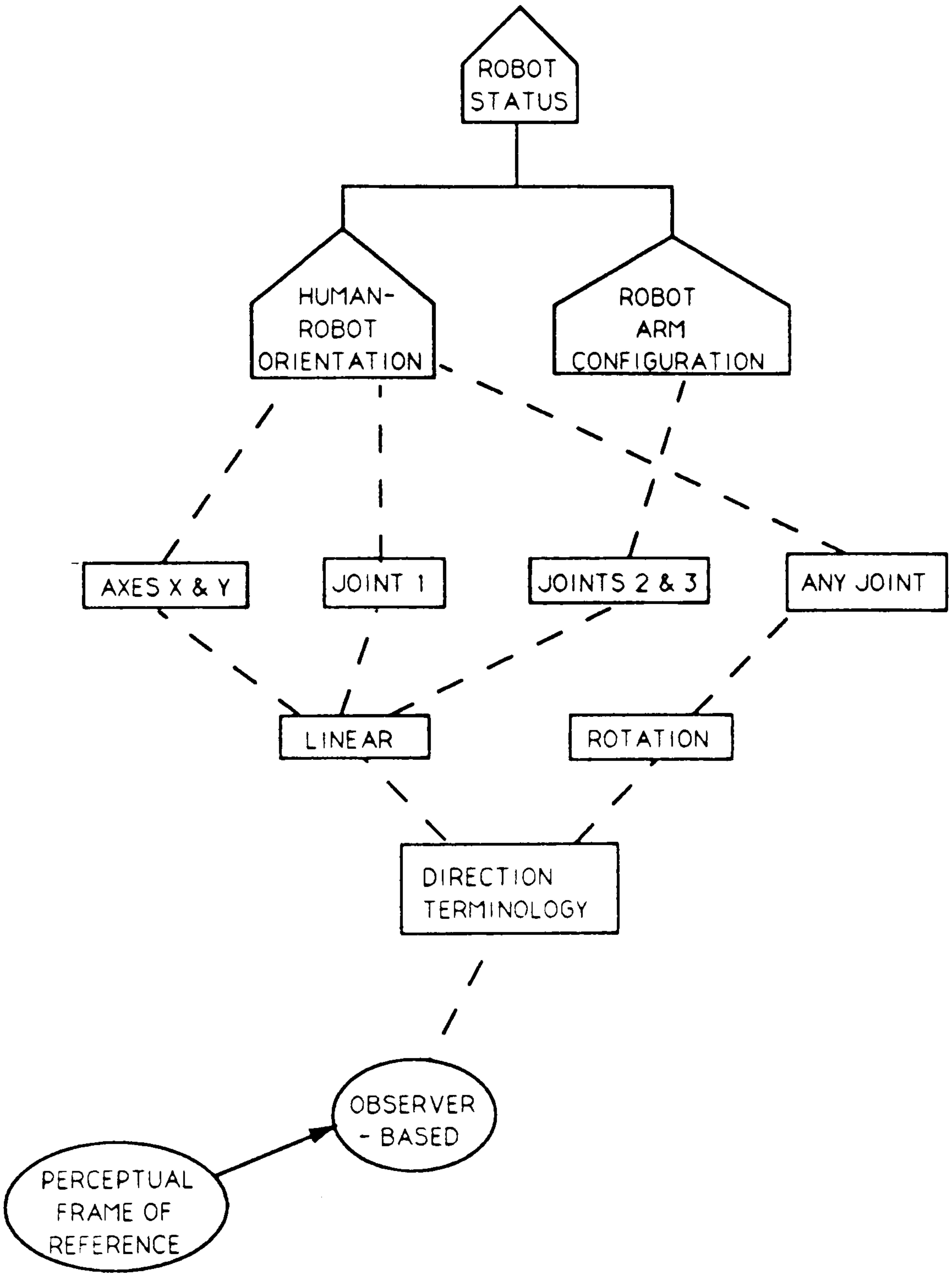
The conditions of motion reversal, indicated by inconsistency in movement descriptions given by observer-based subjects, were further influenced by the direction terminology used to describe robot movement. This is illustrated in Figure 7.4. When the linear movement terminology was used, inconsistent descriptions of world mode movements were produced following changes in human-robot orientation. In joint mode, changes in human-robot orientation produced inconsistent descriptions for joint 1, whereas joints 2 and 3 were affected by changes in robot arm-configuration. When the rotation terminology was used to describe any joint, inconsistent descriptions seemed to be brought about by changes in human-robot orientation but not by changes in robot arm-configuration.

The question of whether inconsistency in movement description truly reflects inaccuracy of status perception is debatable and will be discussed in detail in section 7.2.1. For the purposes of the framework, however, the relationships shown in Figure 7.4 serve to demonstrate the potential conditions of motion reversal for individual degrees of freedom caused by changes in robot status. Whether this causes incorrect control selection is yet another question and will be addressed in the following section.

7.1.4 Perception of control-motion compatibility

In experimental stage 2 the subjects had been asked to make control selections for each robot movement presented to them, as well as verbally describing the movement. The experiment was performed twice by each subject; once using a joystick control and once using a toggle-switch control box. As described in the previous section, in the joint mode experiment (experiment 3) two different terminologies were used to describe robot motion and

Figure 7.4 Conditions of status perception inaccuracy



it was found that there appears to be a connection between description of motion and control selection. Thus, when a descriptor with 'positive' associations was used to describe direction of motion (e.g. right, forward, up, clockwise), the control marked '+' for that particular joint or axis was selected. Conversely, when a descriptor with 'negative' associations was used (e.g. left, backward, down, anticlockwise), the control marked '-' was selected.

In both the joint and world mode experiments, this association was observed for approximately 90% of the control selections made overall (see Tables 6.10 and 6.16). This was the case for subjects using both the robot-based and observer-based perceptual frames of reference. This uniformity of description-control association across all subjects suggests that the ‘observer-based’ subjects would be more likely to make incorrect control selections in a motion control task. They would be expected to make different control selections when the movement was viewed under different conditions of robot status in accordance with their movement descriptions, whereas the 'robot-based' subjects would be consistent in their selections. However, from the results of experiments 3 and 4, it was observed that robot-based subjects may also make incorrect control selections. The reason for this was apparently the motion reference point they had initially chosen for motion description. This determined how a movement would be described (e.g. "clockwise" or "anticlockwise" according to whether the ‘clockface’ was imagined on the front or back of the robot), see discussion of experiments 3 and 4, sections 6.2.3.2 and 6.2.4.2.

Figure 7.5 illustrates the influence of perceptual frame of reference and control-motion compatibility perception on control selection. As was described in the previous section the observer's perceptual frame of reference determines the accuracy of their status perception, demonstrated by the consistency or inconsistency of movement description when viewed under different status conditions. The strong association between movement description and control selection suggests that the subjects' perception of control-motion compatibility was 'description-driven', as described above. Consequently, the 'observer-based' subjects made incorrect control selections when their perception of the movement was inaccurate. Of course, there were some occassions when their perception of robot movement was accurate due to the absence of motion reversals caused by robot status, such as when the arm-configuration was 'normal' (see Figure 5.9) and viewed from the front orientation. On these occasions the 'observer-based' subjects made correct control selections. However, this is not represented in Figure 7.5 as it would over complicate the diagram. The conditions of incorrect selection caused by inaccurate status perception are subject to any relationship between description terminology and robot status, as shown in Figure 7.4.

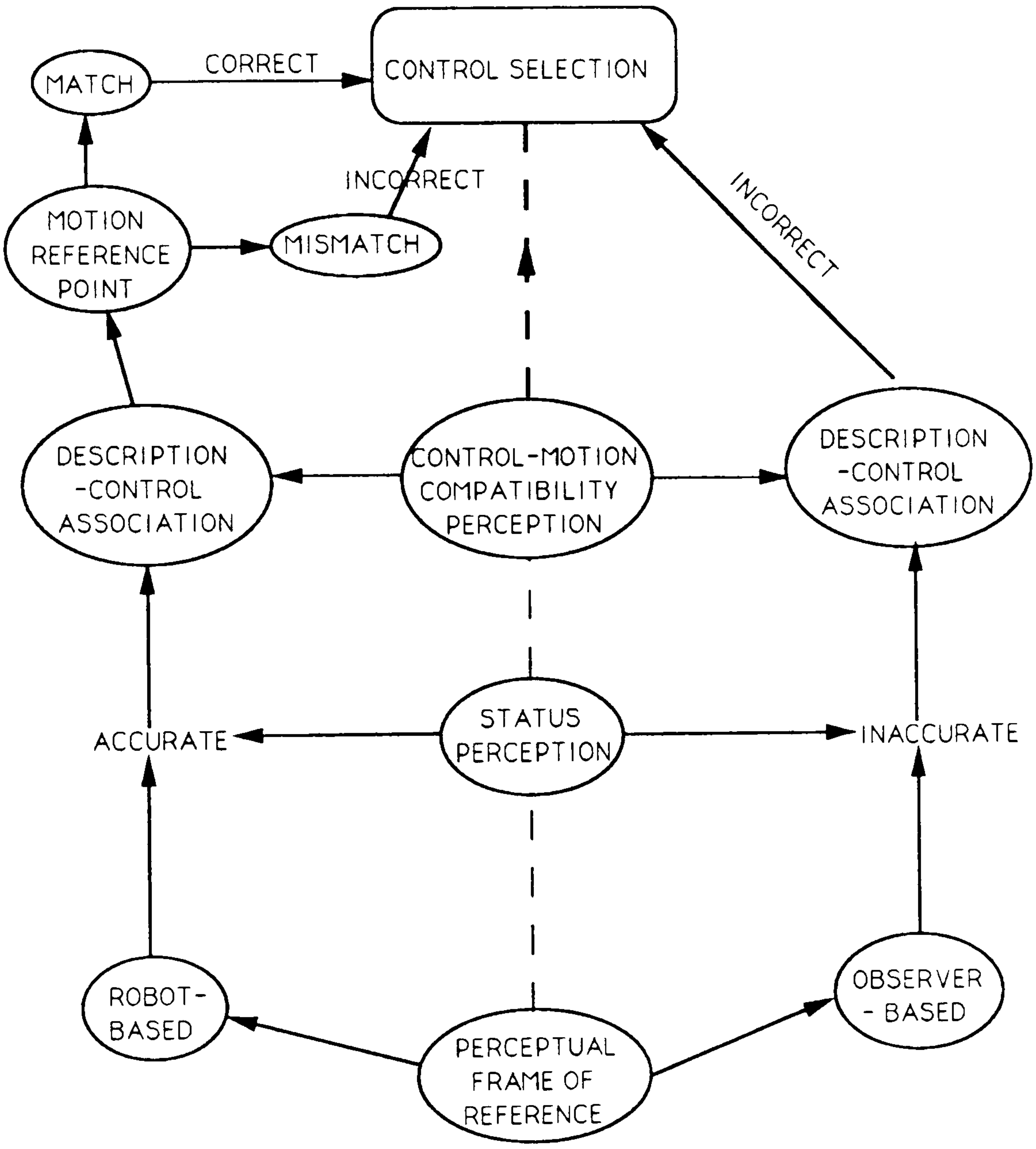
As previously mentioned the 'robot-based' subjects were found to make either consistently correct or consistently incorrect control selections depending upon their initial selection of motion reference point for each degree of freedom. This raised an interesting question as to what the most appropriate motion reference point should be particularly as, in these experiments, the majority of robot-based subjects selected motion reference points that did not match those actually used in practice for the PUMA robot sytsem. This issue will be discussed later in section 7.3.2. Figure 7.5 shows then, that even if a subject uses a robot-based perceptual frame of reference, and therefore demonstrates accurate status perception, because of strong description-control associations, he/she may still make control selection errors if their chosen motion reference point does not match that appropriate to the robot system.

7.1.5 Control performance with motion feedback

The control-selection task used in experimental stage 2 was essentially a stimulus-response task in which the subjects received no feedback of the accuracy of their control selections. Although this method was utilised because of limitations of software interfacing between the experimental controls and the robot system, it was useful as an indication of the user's 'natural expectations' of the control-motion relationship, and it was observed that the subjects expected an association between the direction controls and their description of robot movement. Thus, incorrect control selections were made when the subject's description of a movement did not correspond to the direction of motion established by the robot system designer. For observer-based subjects this occurred when the conditions of robot status were altered and for robot-based subjects it was produced if they initially selected an inappropriate motion reference point.

As explained in chapter 4 (section 4.2), the robot motion control task is not realistically like this, but requires the operator to select a control before the robot movement is observed. The

Figure 7.5 Influence of perceptual frame of reference and control-motion compatibility perception on control selection



development of software interfacing allowing direct robot-motion control using the experimental teach boxes enabled a more realistic task to be examined in experimental stage 3 whereby the subjects received feedback on their control actions. In the joint mode experiment (experiment 5) the subjects were given one of the control boxes (joystick or toggle-switch) and were asked to move individual joints according to instruction as quickly and accurately as possible. Each subject performed the experiment using both controls in each of the arm-configuration positions. In the world mode experiment (experiment 6) the subjects were asked to follow the path of a 3-dimensional maze using both control boxes in each of three human-robot orientations.

It must be emphasised here that we cannot easily measure performance accuracy by observation in the field, since accuracy is defined by how well the actual robot movement matches that intended by the programmer. Only the programmer will know if they have made an error and may not even be consciously aware of it anyway. Since there is rarely, if ever, a unique motion path to achieve a task goal, the programmer may simply amend the next move without correcting the first. In the experiments, therefore, it was necessary to specifically define and experimentally control the robot movements required and then record how well the subjects achieved these movements.

Motion descriptions had previously been used as a means of classifying subjects as robot-based or observer-based, during the experimental task. In experimental stage 3 this was not done as part of the control task but subjects were classified prior to the experimental task using several methods as described in section 6.3.1.1.

Although specific comparison between the experiments in stages 2 and 3 cannot be made, in general, it was noticed that the error rates in stage 3 were much lower and there was little difference in error performance between subject groups. The main reason for this seems to be that, with the provision of feedback of the actual control-motion relationships in stage 3, some of the observer-based subjects changed their strategy for perception of movement directions. This was either by adopting a robot-based perceptual frame of reference or by the use of simple strategies involving environmental cues (defined as using an 'object-based' frame of reference, see discussion of experiment 5, section 6.3.1.4).

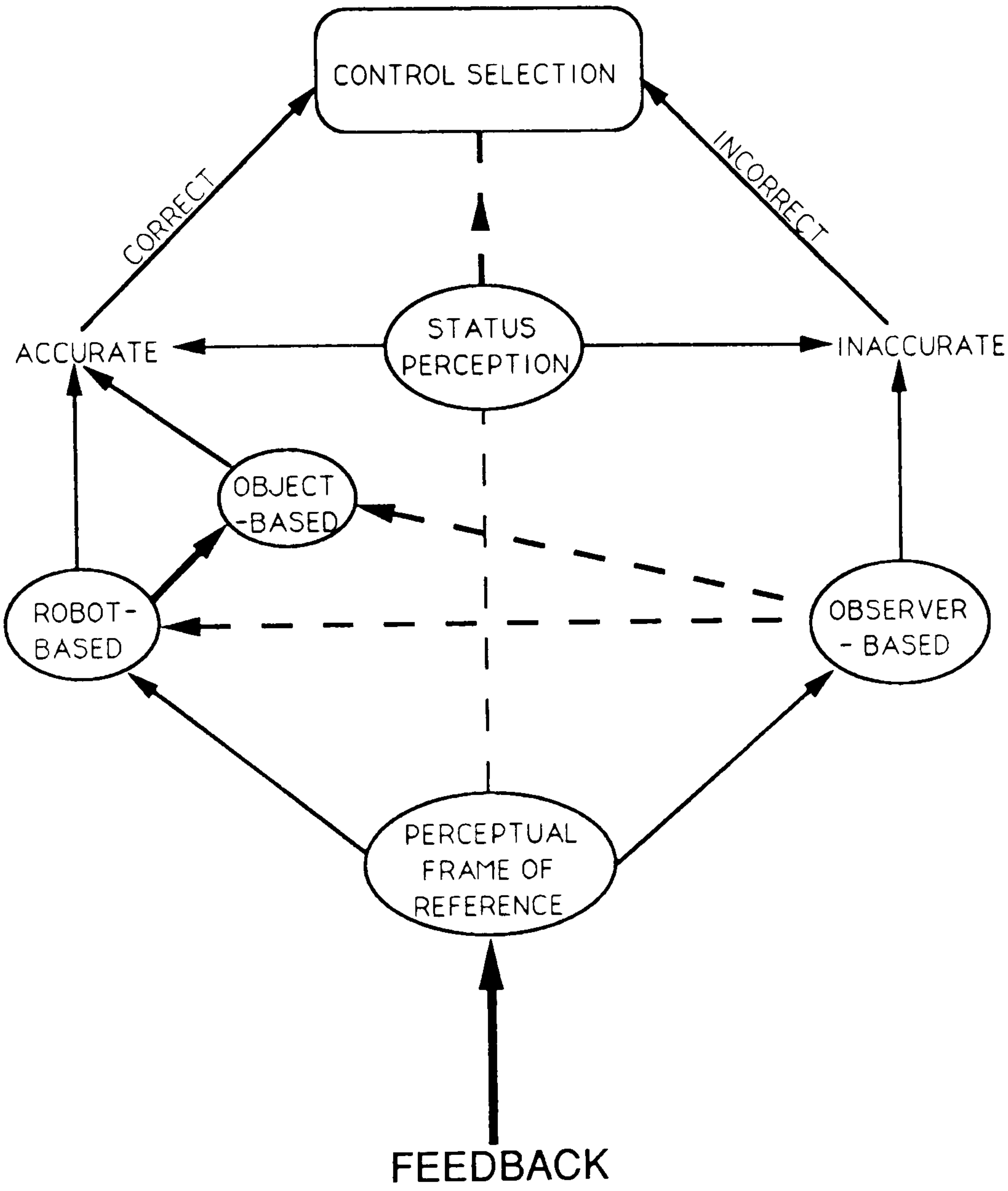
Figure 7.6 shows the effect of feedback on perceptual frame of reference. It can be seen that either change from an observer-based frame of reference (i.e. observer-based to robot-based or observer-based to object-based) will produce accurate status perception and therefore will lead to correct control selections.

In experimental stage 2 it had been shown that for the robot-based subjects, an inappropriate motion reference point led to incorrect control selections. When feedback was provided in stage 3, movement of the robot in an unexpected direction would alert these subjects to their error. To correct for this, they would simply adjust their motion reference point accordingly and thus make correct control selections for the remainder of the task. Thus, the effect of feedback from actual robot movement may be to alter (or reinforce) the observer's perceptual frame of reference.

The use of an 'object-based' strategy inevitably produced correct control selections since the motion reference point is in a fixed position relative to the robot and therefore moves with the robot when status conditions are changed.

It is possible of course that the subjects classed as using a 'robot-based' perceptual frame of reference had actually been using an 'object-based' strategy for motion description all the time. Indeed, during post-experiment interviewing it transpired that half of the robot-based group had done so (see results of experiment 5, section 6.3.1.3 part C subject preferences). This possibility is also illustrated in Figure 7.6. The remaining subjects in this group stated that they did not use environmental cues to help them recognise changes in robot arm-configuration but they had memorised the control-motion relationship when practising with the robot in the 'normal' configuration (Figure 5.9, position A) and related each new configuration to this. This provides a possible explanation for the result that the robot-based subjects took twice as long as the observer-based group to make their control selections. It was assumed that this was produced by the robot-based group having to "think" about their responses and possibly to perform a 'mental rotation' of the robot image to match that of their motion reference point. This issue will be discussed in section 7.4.2.

Figure 7.6 Effect of feedback on perceptual frame of reference



7.1.6 Summary

During the development of the framework representing the robot-motion control process the author considered operator knowledge and cognitive processes to be fundamentally important to performance reliability. These, it was thought, have greater influence than control design per se, which has been the sole consideration in other research work (see section 2.2.3).

The identification of certain conditions of robot status producing 'motion reversals' led the author to consider the user's ability to perceive and recognise these reversals, and the potential effect that this may have on control usability. To this end the experimental work focused on perception of robot motion and control selection under different status conditions. The results have indicated that perception of robot movement *is* fundamental to control selection and that users *may* or *may not* recognise motion reversals depending upon their 'perceptual frame of reference'. In simple control tasks however, such as those used in the experimental programme, strategies for control selection which will reduce errors can be quickly learnt when feedback from robot movement is provided.

7.2 Experimental methodology

The experimental methodology used during the current programme of research was influenced by a number of factors, some technical and others experimental. This section discusses the advantages and limitations of the experimental methodology and makes some comparisons with other methodologies used to measure performance reliability in robot motion control.

7.2.1 Experimental task

The development of the experimental methodology used in the present research was governed largely by the technical resources available. In experimental stage 2, it was not possible to examine users' direct control of robot movement with alternative teach controls and so the method used was to examine their expectations of the control-robot movement relationship in response to given robot movements. This method, although unrealistic, provided information on naive users' 'intuitive' expectations rather than their ability to 'learn' control-motion relationships which may not naturally occur to them. This information was also useful in indicating whether user expectations matched the control-motion relationships of the actual robot system. In fact, the experimental results showed that, for the majority of cases, user expectations did not correspond with the PUMA robot system design, and this is discussed in more detail in section 7.4.3. By the third experimental stage, the software interface had been developed to allow limited control of the PUMA robot with the two experimental teach boxes. This provided the users with feedback of their control selections and therefore provided a measure of their ability to 'learn' the appropriate control-motion relationships for that particular robot system.

Unfortunately, the experimental tasks examined in each of these stages were not the same and so a direct comparison of these two methods and the effect of feedback on control performance cannot properly be evaluated. The inconsistency between the experimental tasks was also a result of the progressive development of the research methodology. In order to measure the subjects' performance in stage 3, it was necessary to develop unambiguous experimental tasks which required the control of specified robot movements. These tasks had to be inherently obvious as it was not appropriate to provide the subjects with verbal instructions; earlier experiments had identified alternative terminologies for describing each robot movement and the selection of one terminology may have proved confusing for subjects who would not use that terminology themselves. In experimental stage 3 the joint mode experiment required movement of individual joints in a specified direction, and the world mode experiment required movement of the TCP along the path of a 3-D maze (see section 5.3.7). In experimental stage 2, for both programming modes, the subjects were presented with a random sequence of individual robot movements, controlled by the experimenter.

A further inconsistency between these two experimental stages was the conditions of robot status in which these tasks were presented. In stage 2, the robot movements were presented at each of four human-robot orientations (front, back, right and left) whereas in stage 3 the world mode task was presented at only 3 orientations (front, back and right side). The joint mode experiment in stage 3 was performed under different robot arm-configurations. This difference in the experimental design was governed mainly by the restrictions of access around the laboratory due to changes in robot guarding out of the experimenters control (described in section 5.3.3).

Finally, an inconsistency existed for the initial training positions used in each stage; these are discussed in section 7.2.2.

One of the reasons for inconsistency across the experimental stages was the complex number of variables present in a realistic robot motion control task. These variables include individual movements (e.g. six degrees of freedom each moving in two directions for three programming modes) in combination with the various conditions of robot status (e.g. four robot arm-configurations and four human-robot orientations) (Figure 5.1, section 5.2). The desire to understand the effect of each of these variables, whilst not confusing the experiments with too many variables, meant that different tasks were necessary in each experimental stage.

If these experiments can be criticised because the control tasks are over-simplistic and unrepresentative of actual control tasks, such simplification has allowed examination of fundamental issues which were thought to influence task performance; the experiments were not measuring overall task performance. This may be the reason why no differences in task performance were observed between the two control designs used. In experimental stage 2, the subjects described robot movements first and then looked for the appropriate control. Thus, they selected the control by its label. In experimental stage 3, although they did not verbally describe each movement, they may have used the same strategy due to the simplistic nature of the control tasks. In consequence of the experimental method used, identification of the potential conditions causing control errors has been possible. This will provide better understanding for later larger experiments with more complicated tasks.

Experiments that have attempted to evaluate control performance on a complete task have done so at the expense of introducing experimental confounding from the many variables included in the task. For example, the experimental task used by Ghosh and Lemay (1985), illustrated in Figure 2.4 and described in section 2.2.3, requires the use of a complex range of robot movements governed by task objectives. The subject is given specific objectives such as; "move robot from position A to position B, pick up peg, move to position C, insert peg into hole". They were not given specific intructions as to what path of movement to follow but were asked to complete the task as quickly as possible whilst avoiding collision with any of the objects in the path. The general path to be taken between the positions is reasonably obvious: however the specific motions to be used and the sequence of these motions were not stipulated by the experimenters and thus were subject to the individual's own path plans. Since the experimenters could not be aware of what the path plan for each subject might be, they had no way of identifying when direction errors occurred unless indicated by the subjects themselves. Furthermore, the lack of control over individual robot movements could have allowed subjects to simply not use movements which they found confusing or avoid moving the robot into a position which would produce motion reversals. Given the complex range of movements available and the conditions under which these movements are 'reversed', as identified during the present research, the experimenters would not be able to assuredly quantify or qualify the direction errors that may have occurred and therefore could not be certain that the same results would be produced if the task were altered in any way.

It is suggested that control tasks involving different robot movements will produce different performance patterns, even using the same teach pendant, because of the different motion reversals that will occur. This may be an explanation for the different recommendations of the 'best' teach pendant design offered by different researchers (e.g. Brantmark et al, 1982; Creed, 1987; Ghosh and Lemay, 1985; Podgorski and Boleslawski, 1990). Although details of the experimental tasks are not provide by Brantmark et al or Podgorski and Boleslawski (see section 2.2.3), it may be assumed that they will have examined different control tasks.

The main advantage of the present research approach, then, is that it provides the basis of a methodology for comparison between alternative control designs, taking into account all the conditions of control-robot movement reversal. With the exception of Creed (1987), who performed only one extremely simple task, these have not been considered by other researchers. A methodology is recommended for further work and is discussed in section 8.2.

7.2.2 Subject training

In all of the experiments a "training" position (human-robot orientation) or condition (robot arm-configuration) is referred to. It must be noted, however, that the subjects were not actually "trained" to perform the task 'correctly' since one of the objectives was to see how naive subjects perceive robot movement and what expectations of the control-robot motion relationship they may have (see section 5.4).

In experimental stages 1 and 2 the "training" consisted of the experimenter showing the subjects how the robot moved (i.e. that each degree of freedom moved in two directions). Except where otherwise explained (see procedure for experiment 2, section 6.1.2.1), no labelling for directional movement was suggested by the experimenter. In experimental stage 1 the subject had been "trained" from the front of the robot. However, during experimental stage 2 a decision was taken to train subjects from the left side of the robot. This was done due to new safety facilities (insisted on by the relevant safety officer and outside the experimenter's control) which limited the space at the front of the robot, thus preventing training at that position. The consequence of this was that subjects used different reference points for their descriptions of directional motion. Whilst this caused difficulty for the interpretation of the experiments, it highlighted the importance of motion reference point selection.

In order to eliminate the confusion caused by "training" at the left orientation, during the third experimental stage "training" was again carried out at the front orientation. This was possible because the subject was seated (joint mode), although extremely cramped, and remained in the same place throughout the experiment. In the world mode experiment, however, the subject was required to move to different positions around the robot for each task. The "training" session again took place on the left side of the robot, but the subject was told that this was the 'front' orientation with the 'right' and 'back' orientations shifted to the actual 'front' and 'right' orientations respectively. This was possible due to the unchanging reference point for world mode movement. A transformation of the X and Y motions was designed into the experiment. Thus, the X control on the teach pendant actually moved the robot along the Y axis and the Y control moved the robot along the X axis. This did not affect the task as far as the subjects were concerned, as the BBC program which converted control selections on the experimental teach boxes into drive instructions to the PUMA robot was altered accordingly.

7.2.3 Classification of subjects

An important outcome of this experimental work was the observation that subjects may differ in their performance because they use different frames of reference for perceiving robot motion. However, the classification of subjects into groups defining their perceptual frame of reference during these experiments needs careful consideration. In the first place, the classification in experimental stages 1 and 2 was made according to the verbal descriptions that the subjects gave of the individual robot movements that were presented to them. This technique is hindered by two major drawbacks;

(i) Verbalisation of robot movement is not a realistic or natural task and is subject to random selection of a terminology (i.e. there may not be a specific domain based reason why one subject uses rotation and another uses linear movement terminology to describe robot motion). Indeed, speech is not a good mode to control spatial tasks generally. This may have introduced an unrealistic aspect to the task which interferes with the way in which users would normally carry it out. Verbalisation of robot movement may draw the subject's attention to their perception of those movements which they would not otherwise consciously think about. This problem is also found generally in "think aloud" methodologies, for instance in mental models research (Rutherford and Wilson, 1991).

(ii) The pattern of description "errors", defined as inconsistency in describing an individual movement when viewed under different conditions of robot status, may not necessarily represent the subject's inability to recognise that the movement is the same. For instance, if a joint movement is described as "up" when in the RIGHTY arm-configuration but "down" when in the LEFTY arm-configuration, this may reflect a tendency for the subject to merely 'report-what-they-see'. It may not mean that the subject actually perceives that the joint is moving in a different direction. This question was raised in section 7.1.3 where it was assumed that inconsistency in movement description reflects inaccuracy of status perception. Support for this assumption was produced in the second experimental stage in which the subjects made control selections in addition to describing individual robot movements. The strong association between description of movement and control selection suggests that the subjects' descriptions *did* reflect their perceptions; otherwise they would not have made different control selections for the same movement when viewed under alternative status conditions. Thus movement description was accepted as a reasonable indication of robot status perception.

7.3 Cognitive factors affecting performance reliability

7.3.1 Perceptual frame of reference

The notion of observers using a perceptual frame of reference on which they base their decisions concerning direction of robot movements is similar to the frames of reference described by Shepard and Hurwitz (1984). They distinguish three different frames of reference from which orientation and movement direction can be defined;

"(a) an egocentric frame defined by the directions of up-down, front-back, and left-right with respect to one's own body...;

(b) an object-centred frame similarly defined with respect to some other person, animal, or object....on the basis of its own intrinsic top and bottom, front and back, and left and right sides; and

(c) an environmental frame defined by the directions of up-down, north-south, and east-west conferred on a particular location of the surface of the earth..." (p. 162)

These frames of reference can be directly related to the perceptual frames of reference defined in the present research whereby the 'egocentric' frame describes the performance of the 'observer-based' subjects and the 'object-centred' frame describes the performance of the 'robot-based' subjects for robot movement in joint mode. The 'environmental' frame can be related to the directions of robot movement in the world programming mode since they are fixed in relation to the 'world' or 'environment' irrespective of the egocentric or object-centred frames of reference described above. Thus, this frame describes the performance of the 'robot-based' subjects for robot movement in world mode.

It should be noted that, for the object-centred reference frame, the robot is the object being referred to. This should not be confused with the definition of an 'object-based' strategy as described by the author in section 7.1.5, which was meant to refer to objects other than the robot whose position and orientation on the robot arm provided cues to changes in robot status (e.g. the orange wires near the gripper and the PUMA legend on the outside of joint 2).

Similar concepts are used in navigation to identify the direction of movement of a vehicle (e.g. Aretz, 1989). Two frames of reference are described;

i) The ego-centred reference frame (ERF) or "inside-out" view that is established by the forward view out of the vehicle. In this case, navigational decisions are made relative to the traveller's forward field of view (Wickens, 1990), thus 'right' and 'left' turns correspond to the right-left directions defined by the egocentric frame of reference.

ii) The world-centred reference frame (WRF) or "outside-in" view that is established by the vehicle's location on a map. In this case, navigational decisions are usually made relative to North in accordance with the environmental frame of reference.

It is not hard to recognise the confusion that may arise when a traveller heading South is following his course on a map which is designed to show North up; a 'right' turn on the map requires a 'left' turn in the operator's forward field of view. For this reason Wickens (1987) recommends that navigational displays should be compatible with the operator's viewpoint and this particular problem has been solved by the use of frequency-separated 'heading-up' displays whereby the steady direction of the vehicle is always displayed as 'forward'. Wickens (1987), citing the work of Fogel (1959), Roscoe and Williges (1975) and Roscoe (1980), describes how the heading-up display works; "Using the frequency-separated algorithm, rapid changes in display properties are driven by the outside-in principle, whereas relatively low-frequency changes are driven according to the inside-out principle. .... Consider a navigational display in which the vehicle is heading 'up' the display. If the vehicle turns to the right, a high frequency change, the vehicle symbol also turns to the right. If it maintains this new course, a lower-frequency behaviour, the entire map now slowly rotates counterclockwise until the vehicle's new heading is again upward" (p.79).

The use of such 'track-up' displays simplifies navigational decisions since both the ERF and WRF are aligned in the same direction. However, Aretz (1989) suggests that 'track-up' displays are not always feasible and the inevitable incongruency between ERF and WRF requires a cognitive transformation by the operator to mentally align the two frames of reference.

A similar interpretation was made of the results of experiment 5 (stage 3, joint mode) to explain why the robot-based subjects had taken significantly longer to make their control selections than the observer-based subjects (see section 6.3.1.3, B, analysis 4). It was suggested that, under conditions of motion reversal, the robot-based subjects performed a 'mental transformation' of the robot image to match their reference point (i.e. the training condition; position A), and this may require extra 'thinking' time (see section 6.3.1.4). If we assume that, in the training condition when the subject establishes his/her understanding of the control-motion relationship, the ego-centred and object-centred reference frames are aligned, then changes in robot status will cause incongruency between the two reference frames. In order for the robot-based subjects to make a consistent control selection for a movement viewed under different conditions of robot status, they may need 'mentally' to bring the two reference frames back into alignment. Depending upon the type of status change (i.e observer movement or robot arm re-configuration), they may try to 'imagine' themselves back in the training position or the robot arm back in its original configuration before they are able to make their control selection. In the post-experiment interviews, half of the robot-based subjects stated that this was the approach they had used, whereas the remaining half used environmental cues to help them remember directional movement (see section 6.3.1.3, C).

7.3.1.1 Mental rotation

Some psychologists argue that mental rotation is the cognitive process by which the operator aligns two frames of reference. In a number of studies Shepard and colleagues have examined the mental rotation of internally imaged objects (e.g. Shepard and Cooper, 1982; Shepard and Metzler, 1971). They have also developed the mental rotation test (MRT), examining subjects' ability to manipulate two-dimensional representations of three-dimensional shapes (line drawings) in space, by mental rotation. They have found that the time required by subjects to visually compare two stimuli for identity increased linearly with the angular difference between their orientations. In a later study, Shepard and Hurwitz (1984) found that, in map reading, the identification of a turn as a right or left turn, takes increasingly longer as the direction of the line going into the turn departs further from upright. The extreme case of 180° departure, as in reading a completely inverted map, was consistently the most difficult. Shepard and Hurwitz argue that the delay in reaction times, being a function of the angular displacement of the target, demonstrates an additional cognitive operation in the identification task. This cognitive operation is claimed to be specifically one of mental rotation. Furthermore, they claim that imagining the reorientation of an object is more effective than trying to reorient one's egocentric frame of reference.

If robot operators have mentally to rotate the robot image from its current position to some index or norm position before activating controls to achieve a task, then response times recorded for robot-based subjects might be found to follow a similar relationship of increase with angular deviation as that found in the experiments reported by Shepard and Cooper (1982) and Shepard and Hurwitz (1984). Looking at the results of experiment 5 (stage 3, joint mode) given in section 6.3.1.3, B, analysis 4, as expected, the effect of configuration on subject response times was significant for the robot-based group but not for the observer-based group. For the robot-based group, although response times were significantly higher in each of the alternative configurations (B, C and D) than in the training position (A), there were no significant differences between the response times at the alternative configurations. However, the three alternative configurations do not represent different degrees of rotation of the robot arm from its original position. Each configuration change presented a different type of rotation from the original position; A-B was produced by rotation of joint 1; A-C was produced by rotation of joints 2 and 3; A-D was produced by rotation of all three joints. These different types of configuration change may be equally difficult for mental rotation. Therefore, it is not possible from this research programme to strongly support the notion that the time for mental rotation of an image increases linearly with the amount of rotation required.

It was considered that there may be some connection between the MRT task and recognition of the robot under different status conditions; that is, both tasks may involve the same kind of mental rotation abilities. An additional task therefore was presented to the subjects who participated in experiments 5 and 6. After they had completed the experiment (both sessions) they were asked to complete the MRT test under the appropriate conditions (i.e. a six-minute time limit for undergraduate students). The MRT scores were then correlated with the subjects' classification groups (robot-based or observer-based) identified prior to the robot control task. It was hoped that if high correlations were found, and therefore that the two tasks represent the same types of ability, the MRT test could then be used subsequently to determine the operators' perceptual frames of reference without going through the lengthy and tedious process of having the observer describe robot movements under different conditions. Unfortunately, no correlation was found between MRT scores and subject classification for either the pre-experiment or post-experiment groupings. This is possibly because the two-dimensional representation of three-dimensional objects (used in the MRT test) perhaps does not present the same task as actual recognition of a three-dimensional object in different orientations. Although Shepard and Metzler (1971) showed that subjects do recognise the line drawings as three-dimensional shapes, these shapes vary considerably from the three-dimensional form of the robot arm, from which added cues such as shading, perspective and stereoscopic visualisation may be used.

Just and Carpenter (1985) suggest that, in mental rotation tasks, the issue that has still not been resolved concerns the content of the rotated representation. It could be that a representation of the entire object is rotated or just a subset of the object. Presson (1982) suggests that the content of a mentally rotated image depends upon the type of information required. In an experiment in which an array of labelled blocks were to be 'imagined' following a rotation of either the array itself or the observer in relation to the array, it was found that when asked questions about array appearance or the position of a specific block, subjects rotated only the relevant part of the array. However, when asked which block would occupy a specific position, rotation of the entire array was necessary.

It has already been mentioned that the robot-based subjects in experiment 5 reported using one of two methods to identify changes in robot arm-configuration (see section 6.3.1.3, C). One method, described in the previous section, was to internally 'image' the whole of the robot arm in its original position and relate directional movements to the new position. The other method was to use cues on the robot arm, such as wires, labels, etc., and relate directional movements to them. Thus, it would seem that these findings confirm the suggestions of Just and Carpenter (1985) and Presson (1982) whereby the content of the rotated representation of an object can be either the whole robot arm or a relevant subset of the robot (e.g. wires or labels). However, in the present research, this was found to be subject to individual differences between observers.

7.3.1.2 Teleoperator control

Teleoperation is very similar to robot motion control insofar as a remote control is used to operate a manipulator arm with several degrees of freedom. A major difference between the two operations is that, in teleoperation, the operator can be so far removed from the manipulated element that control feedback is often not available via direct viewing, but is supplied by a monitor display from a camera located at the work site, or by a graphic 'predictor display' of status and movement (Book, 1985; Sheridan, 1987).

This distinction separates the two operations in terms of the control problems they present to the operator. With respect to the perceptual problems described in the present research, teleoperation in robotics (e.g. in space, hazardous environments, etc.) does not necessarily involve the same changes in robot status since the camera through which the robot is observed is usually placed in a fixed position relative to the robot. Sometimes the camera is actually fixed on the robot arm. In this case the operator views the environment 'as if he/she *is* the robot' and the egocentric and object-centred reference frames are continuously aligned. However, Wickens (1987) suggests that, in contrast to his recommendation for navigational displays, motion control of a remotely operated robot would be easier if the image were an "outside-in" picture rather than an "inside-out" picture from a camera mounted on the robot itself. This, he suggests, is because the operator assumes the robot to be the moving element in a stationary world. As the camera will always be facing the robot from the same orientation this may be true for types which cannot change arm-configuration, but will still present problems for those which can.

The use of teleoperator displays presents the operator with different kinds of problems related to clarity of the display image, display type, feedback type and consequences of delay; much of the literature concentrates on these issues (e.g. Bicker et al, 1988; Stark et al, 1987). However, the work of Smith et al (1990) has shown that control performance is better when the camera is positioned in a 'normal' orientation relative to the robot such that the operator can use the body of the manipulator as a reference point for motion directions; performance deteriorates when the camera is placed at other orientations.

7.3.2 Perception of control-motion compatibility

In the current work strong associations between control selection and description of movement were observed for all subjects regardless of whether or not their descriptions were consistent with the *appearance* of robot movement. The strength of these associations implies that even naive subjects use a control selection strategy that is logical. The major difficulty for robot motion control, then appears to be a perceptual one, concerned with recognising which degree of freedom is to be moved and in which direction, relative to an index or norm position. Having made these perceptually-based decisions, selection of the appropriate control is not difficult with limited control sets; the operator makes use of simple selection strategies such as "+ve = up, right or clockwise". However, these decisions may become more complex as the number of operations per control is increased.

An experiment to examine different conditions of display compatibility with changes in physical position was carried out by Worringham and Beringer (1989). A target aquisition task was performed under three different conditions of compatibility; visual-motor, in which the direction of movement matched the direction in the observer's 'virtual' visual field (i.e. the subjects looked at the display rather than the control); visual-trunk, in which the control movement was in the same direction relative to the subject's trunk as the movement of the display in the visual field; and control-display, in which the control and display movements were in the same direction. On all movements, the performance was fastest under conditions of visual-motor compatibility. The authors suggest that control-display compatibility is only suitable for tasks in which the control and display are consistently aligned, and that visual-motor compatibility is more applicable to tasks in which many different operator positions may be adopted. This may help to explain the results of the present research, described above, whereby the subjects did not move the controls in the same direction as robot movement. They expected a control-motion relationship that was compatible with how they *perceived* robot movement irrespective of any incongruences between the physical control-motion directions.

7.4 Robot system factors affecting task difficulty

7.4.1 Robot status

Robot status has been defined in this work as the combination of conditions of robot arm-configuration and human-robot orientation; these individually and in combination, cause reversals of robot movement directions with respect to the operator. As such, robot status is probably the most important factor affecting task difficulty in robot motion control. The consequences of movement reversals were discussed in detail in sections 7.1.3 and 7.1.4 where it was shown that 'misperception' of robot status can lead to incorrect control selection.

Although other machines may share some of the same movement capabilities as robots (e.g. cranes), the position of the motion controls relative to the machine generally remains the same. Thus, it is desirable that there should be a logical control-motion relationship, and the operator is simply required to learn this relationship. It has been shown that operators are able to learn incompatible control-motion relationships. However, contraventions of control-motion stereotypes such as those described in section 3.5.3, may lead to control errors when the operator is placed under conditions of stress or distraction (for examples, see Murrell, 1965).

The fundamental difference between robots and other types of (remote) motion control is that the orientation of the controls to the parts of the robot they operate is not consistent during the programming task; the problem of motion reversals is unique to robotic systems. Furthermore, the possible conditions of motion reversal are specific to particular robot types. The jointed-spherical type robot is the only one capable of arm-configuration changes such as those described in this work. However, for all but the cartesian coordinate type robot, the main arm can be rotated about its base producing possible left-right, clockwise-anticlockwise reversals of the remaining degrees of freedom. In all cases, subject to workplace layout and task requirements, the operator is likely to perform robot motion control from any human-robot orientation. Thus, the motion reversals that occur under these conditions are relevant to all robot types.

The three degrees of freedom used for tool orientation (i.e. joints 4, 5 and 6) present additional conditions of motion reversal of much greater complexity than has been possible to examine during the course of this research. For example, the wrist motions can be reversed according to the orientation of the wrist itself or as a result of reversals produced by the positioning joints (joints 1, 2 and 3).

As was explained in section 7.2.1, it was not possible to examine all of the variables in the motion control task in this research work. However, the identification of factors which influence control performance (i.e. robot status and status perception, determined by the observer's perceptual frame of reference), will enable better understanding of performance reliability in other conditions of robot control. For example, the alternative robot status conditions can be presented in the form of a chart, such as that given in Appendix V. The direction of joint motion can be added as shown to provide an illustration of the *appearance* of each movement in each status condition. This chart can be used to determine;

i) how a movement may be perceived by the operator (according to different description terminologies), and

ii) the control-motion relationship for alternative teach control designs and how this is changed in each of the status conditions.

Furthermore, the same method can now be applied to other degrees of freedom, producing a complete description of robot movements in all possible status conditions for any robot system. This information will be useful for the identification of motion reversals within realistic control tasks, which may help to explain the cause of control errors. In addition, it can be used for the design of experimental tests to examine specific aspects of control tasks. These issues lead to recommendations for further work and are presented in section 8.2.

7.4.2 Control-motion compatibility

As described in section 2.2.2, the ANSI/RIA proposed standard for robot teach pendant design states that the controls should be designed such that, "Actuation of a control corresponds to the expected control-movement direction and be oriented so that the control motions are compatible with the movements of the robot" (ANSI/RIA, 1988, para. 5.3.1). However, there are several reasons why control-motion compatibility for the control of robot motion cannot be achieved.

The first concerns the current convention of multiple-mode controls. As was explained in section 3.4, it is usual that the motion controls on a teach pendant are used to drive the robot in all available programming modes with the mode initiated by pushbutton selection. Thus, the same control action can produce at least three different motions of the robot arm. Figure 7.7 illustrates the motions produced by the same control actuation in each programming mode, using the toggle-switch and joystick control designs. These control-motion relationships for joint and world modes were described in section 3.5. For the joystick control, being only a three-axis control, the number of motions per control is doubled since each control operates two degrees of freedom within the same programming mode, according to the position of a toggle-switch next to the joystick. With the robot positioned as shown, rotation of the joystick in the clockwise direction will move, in joint mode, joint 3 upwards when the toggle-switch is up or rotate joint 6 away from the observer when the toggle-switch is down. In the world and tool modes, it will move the TCP along the Z axis when the toggle-switch is up or rotate the TCP around the Z axis when the toggle-switch is down. These latter motions are illustrated in Figure 7.8.

Figure 7.7 Robot motions in each programming mode produced by one control action using two alternative control designs

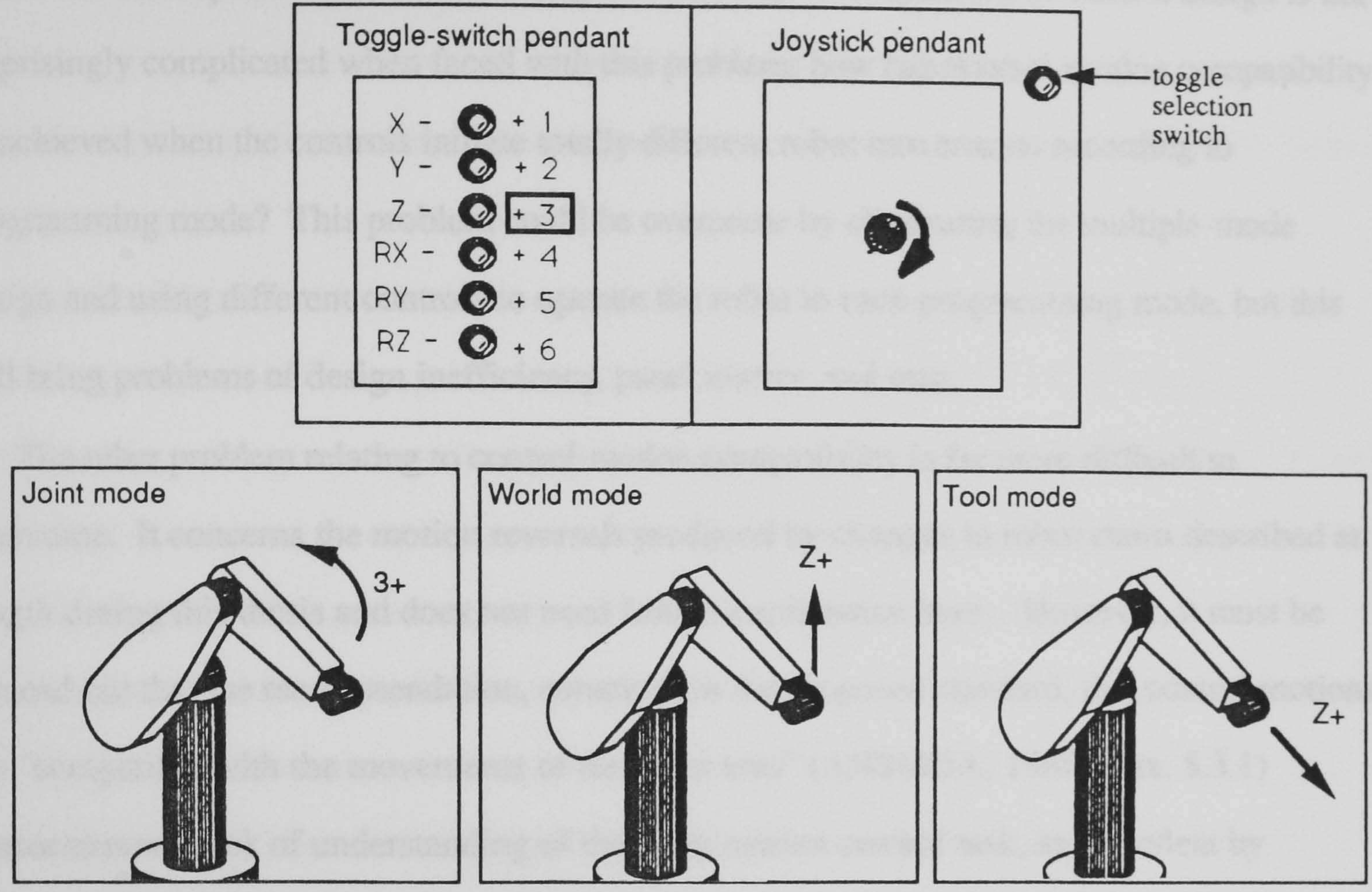
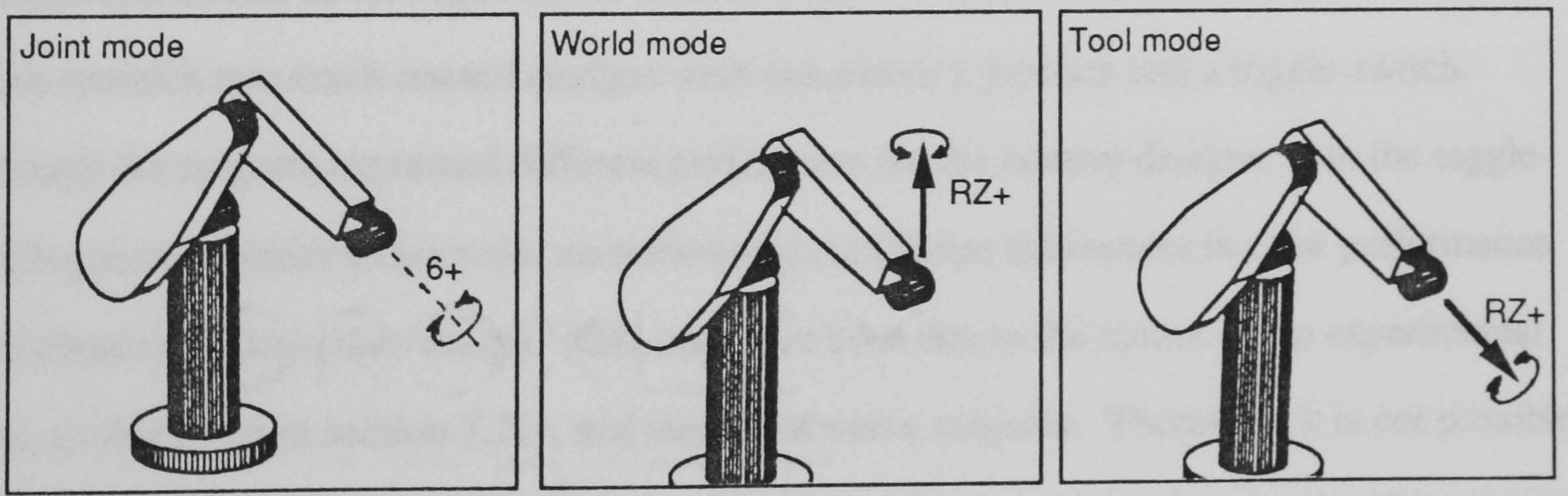


Figure 7.8 Robot motions in each programming mode produced by the same control action using the joystick, but with the toggle selection switch in the down position



Although control-motion compatibility is not evident in any of these cases, it can be appreciated that, even if control-motion compatibility were achieved for one of the motions, it would not correspond with the remaining two motions. The question of control design is not surprisingly complicated when faced with this problem; how can control-motion compatibility be achieved when the controls initiate totally different robot movements according to programming mode? This problem could be overcome by eliminating the multiple-mode design and using different controls to operate the robot in each programming mode, but this will bring problems of design inefficiency, panel clutter, and cost.

The other problem relating to control-motion compatibility is far more difficult to overcome. It concerns the motion reversals produced by changes in robot status described at length during this thesis and does not need further explanation here. However, it must be pointed out that the recommendation, contained in the proposed standard, that control motions are "compatible with the movements of the robot arm" (ANSI/RIA, 1988, para. 5.3.1) demonstrates a lack of understanding of the robot motion control task, as is evident by consideration of the control-motion relationships for the movements illustrated in Appendix V.

7.4.3 Teach pendant design

The ultimate aim for research evaluating teach pendant usability in robot motion control is to identify the optimum control design that will maximise control reliability and efficiency. Whether this should be through control standardisation is another issue and is discussed later. In this research two teach control designs were examined; a joystick and a toggle-switch. Although the subjects expressed different preferences for the control designs; with the toggle-switch generally easier to learn on, no statistically significant differences in error performance were observed using either design. This may have been due to the nature of the experimental tasks, as described in section 7.2.1, and the use of naive subjects. Therefore, it is not possible to offer specific recommendations for control design. However, some issues related to motion control design have been identified during the work and these raise important questions concerning control design requirements.

The first issue relates to control-motion compatibility. The problems of achieving this were discussed in the previous section and the question that arises is; should designers strive for control-motion compatibility *at all* when compatibility in one situation may cause incompatibility in another? Perhaps it would be more appropriate to design for a control-motion relationship that is compatible with *perceived* robot movement as discussed in section 7.3.2.

The second issue relates to the convention of using the same controls to operate robot movement in all available programming modes, also discussed in the previous section. It is suggested here that, given the different types of motions produced by each programming mode (described in section 3.2), different control designs may be more suitable for each mode. For instance, the joystick may be more appropriate to world mode movement because of the control-motion compatibility it offers at one human-robot orientation. This relationship could be maintained at other orientations by the operator rotating the entire joystick assembly to match a particular orientation. However, this solution is not readily applicable to joint mode movements as the control-motion relationship is affected by changes in arm-configuration as well as human-robot orientation, see Appendix V. Thus, the question still remains as to how desirable it may be to provide control-motion compatibility in one programming mode when this cannot be achieved in others.

The third issue concerns the control-motion relationship for different robot systems. In addition to control design variation, it was noted that robot systems also differ in the control-motion reference points that are appropriate for accurate 'perception' of robot movements. Of particular relevance is the mistaken assumption made by Creed (1987) that "Teach pendants are designed to be used from the front of the robot" (p.2). In fact, during the course of this research, it was discovered that the two control designs being compared differed in this respect; for the PUMA robot system the teach pendant *is* intended to be used from the front of the robot, whereas for the ASEA robot it is designed to be used from the left side. This has implications for control performance when an operator is required to use different robot systems. Following the argument of Edwards (1984), that ‘negative transfer’ of learning will occur when using different control designs, the same problem may arise even if the same control were used to operate different systems. For example, if a joystick control were used to operate both of these systems, the X and Y axes labelling would be different in each case. For the PUMA system movement along the X axis would be achieved by moving the joystick to the left or right, whereas for the ASEA system it would be achieved by moving the joystick forward or back. The absence of direction labelling on the joystick may confuse the operator still further.

The fourth issue relates to the choice of motion reference point and its subsequent effect on direction labelling. The choice of +/- joint directions in the PUMA robot system, although conforming to mathematical logic, is the reverse of the expectations of the majority of subjects for some joints (see discussion of experiment 4, section 6.2.4.2). In experiment 4 it was found that, even if a subject uses a robot-based perceptual frame of reference and therefore is not confused by direction reversals, they can still assume an initial reference point which produces incorrect control selection because it does not match the reference point appropriate to the robot system. Different robot systems may also vary in this respect.

All of these issues require further work before suitable recommendations for control design can be made.

7.5 Other issues

7.5.1 Operator training

One of the first problems that faced the design and running of experiments in this work was the lack of standard terminology for describing and defining robot movement. In addition to the variety in teach pendant labelling (e.g. joints may be defined by numbers, letters or legends and motion direction can be defined by symbols, legends (+/-) or words (left, up, out etc)) it was found that this problem extended to the description of joint motion provided in the programming manuals. For example, in the Unimate PUMA system the teach pendant controls are labelled with joint numbers (1,2,3,4,5,6) whereas in the programming manual (Unimation Inc., 1978), the joints are described in words (waist, shoulder, elbow, pitch, yaw, roll). Motion directions are denoted using +/- legends on the teach pendant and described in the manual, incorrectly it should be noted, as follows; "Moving the switch to the left (+) will move that joint left or up (depending on the joint and its orientation). Moving the switch to the right (-) will move the joint right or down (depending on the joint and its orientation)." (p. 3-16). Given this programming manual to work from, a trainee programmer will inevitably become confused by the mixed terminology and would have great difficulty in correctly identifying the control-motion relationships. Furthermore, it is unlikely that he/she will receive adequate training from the robot supplier.

In a study of 16 robot user companies in Britain, Edwards (1984) found that training for robot programming and maintenance tasks was generally carried out in the training departments of the robot suppliers, and was included in the purchase price. However, the user companies expressed dissatisfaction with the quality of these training courses on the grounds that they were 'superficial' and ineffective. One robot programmer, spoken to during the field observations of the present work, stated that during his training course (at Unimation, UK), the manufacturers merely described the programming procedure and demonstrated some of the programming commands. No real guidance on the use of the motion controls was offered; the users were expected to learn by trial and error. Indeed, when a representative from Unimation visited the Nottingham research laboratory and the issues being examined were demonstrated, he said that he had been teaching programmers for over twelve years and had never actually thought about the problem in this way; he still had to 'guess' which way the arm would move when operating the teach controls.

The findings of this research suggest that training may be required to help the operator correctly perceive robot movement. For example, the experimenter found that during the course of the work she developed a simple strategy for defining +/- directions of joint movements. This was to identify whether the robot was in a RIGHTY or LEFTY arm-configuration. When in a RIGHTY configuration '+' movements of joints 2 or 3 would appear to move the arm upwards. When in a LEFTY configuration the arm would move downwards following the same control movement. Training programmers to use this strategy may therefore simplify their decision-making for correct movement planning of these joints.

7.5.2 Control standardisation

Standardisation of robot motion controls has been requested in the interests of improved performance reliability and programmer safety (Cousins, 1989; Parsons, 1988; Rahimi and Azevedo, 1990). However, it has been argued that the current design guidelines for teach pendants are lacking in terms of recommendations for motion control design. The guidelines, such as they are, make general recommendations on the basis of design principles but these reflect little consideration of the actual programming task. For instance, they ask for control-motion compatibility in compliance with user expectations but offer no guidance on how this is to be achieved or assessed (ANSI/RIA, 1988; HS/G 43, 1989).

It has been shown that control-motion compatibility cannot be achieved with multiple-mode controls, and that even if each control were to operate only one mode, compatibility cannot always be maintained under changing conditions of robot status.

Previous experimental research provides limited, and sometimes conflicting, recommendations for the most suitable control design (Brantmark et al, 1982; Creed, 1987; Ghosh and Lemay, 1985; Podgorski and Boleslawski, 1990). This is because their experimental tasks have been too general and have not accounted for the conditions of motion reversals. It is important that further work should address these issues and that a detailed study of control performance using different control designs under all possible conditions of programming is carried out before recommendations for control standardisation can be made.

Furthermore, in order to be effective, standardisation should be considered beyond the physical control design and include standard motion reference points and direction-of-movement labelling between robot systems.

7.5.3 Off-line programming

The world of industrial robots is changing fast. Robot reliability and flexibility are increasing rapidly as developments in sensor technology and control software are improving. In the USA it has been forecast that 60% of all robots are expected to utilise sensory devices and half of all computer controlled robots will be programmed using off-line methods by 1995 (SME, 1985).

This does not mean, however, that the use of teach pendants will become obsolete, but only that the nature of their use will change. The development of off-line programming may eventually make the program control aspect of teach pendants redundant, but the facility for direct drive of robot motion will always be needed, at least for fine tuning and program testing. For cost reasons, manufacturers will not readily change the design of their teach pendants unless forced to do so by law or safety standards. The attraction of off-line programming methods may create a suitable chance for new teach pendant designs to be introduced. For example, the teach pendant could be front-ended to a computer-aided design (CAD) system to facilitate drive of the robot model. In the interests of safety and reliability, it is desirable that there is standardisation in motion control design and that the design chosen is that which produces minimum errors. If less time is spent at the point of operation, the reduction in the amount of close human-robot contact may tip the balance of teach control standardisation being advantageous more to reliability than to safety but does not render it any less desirable. As stated by Deisenroth (1985); "Although the future is quite bright for developments in off-line programming areas, the teach pendant method has not yet even begun to fade. At present it is, and will remain for some time, the most widely used programming method of computer-controlled industrial robots." (p. 365).

CHAPTER 8 - CONCLUSIONS

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8.1 Conclusions

The programme of work reported here was set up to examine the task of robot motion control using a teach pendant, to identify factors which may influence control reliability and to assess the effect of these factors on control performance. The major findings have been as follows.

1. The motion control task was found to involve a series of decisions, at different levels, concerning robot movement. First, and at the most general level, the path of movement is defined. Secondly, the type of motion (programming mode) is decided, and finally the individual movements (degrees of freedom and direction-of-movement) are selected. In association with these last two decisions, appropriate controls on the teach pendant must be activated.

2. Operator knowledge and cognitive processes were thought to be fundamentally important to performance reliability. It is concluded that these have greater influence on control selection errors than control design per se, which has been the sole consideration in other research work.

3. A framework has been developed to represent the motion control process, showing the decisions and actions required together with the factors which influence them.

4. Two types of influencing factors have been identified: robot system factors and human cognitive factors. Robot system factors were found to add complexity to the control task by producing motion reversals under certain conditions of robot status. However, it is the operator's perception of these conditions that influences their decisions and subsequent control selections.

5. Robot status has been defined as the combined conditions of human-robot orientation and robot arm-configuration. These conditions can alter the relationship between control movement and robot motion.

This is made more complicated by the fact that motion reversals for different robot movements, and in different programming modes, occur under different robot status conditions. Thus, it is impossible to achieve consistent control-motion compatibility.

6. The conditions of motion reversal have been identified for the major degrees of freedom in joint and world programming modes. These are represented in chart form.

7. These motion reversals alter the *appearance* of robot movements as viewed by the operator. This can cause 'misperception' of movement and therefore errors in deciding what a required movement is (movement planning).

8. Incorrect movement planning may lead to control selection errors. These are not generally made in joint/axis identification, but in recognising the correct direction-of-movement required.

These control errors arise because of contradictions, due to motion reversals, of the expected association between *perceived* direction-of-movement and control labelling.

9. Control labelling for different robot systems varies, partly in respect of different terminologies for defining direction-of-movement, and also in the motion reference points from which movement directions are defined. This may confuse operators when they are required to control different systems.

10. Perception of robot movement is determined by the operator's perceptual frame of reference.

Two frames of reference have been defined: robot based, in which movements are consistently defined in relation to the robot; observer-based, in which movements are defined in relation to the observer.

The use of a robot-based frame of reference indicates comprehension of robot status changes, producing consistent control selections for individual robot movements.

The use of an observer-based frame of reference indicates a lack of comprehension of robot status changes, producing inconsistent control selections for individual robot movements.

11. Feedback through observation of actual robot movement can influence the perceptual frame of reference used for perceiving robot motion.

12. Two teach pendant designs (joystick and toggle-switch) were experimentally examined in this research; no statistically significant differences were found in errors made, and thus in reliable performance. Therefore, it is not possible at this stage to offer specific recommendations for control design. In any case, this research has shown that our state of knowledge is not yet sufficient to make definitive design recommendations. For instance, the incidence of motion reversals has raised an important question concerning the desirability of control-motion compatibility, which is requested in current design guidelines.

8.2 Recommendations

1. The problems arising within operator cognitive processing in robot motion control suggest that control performance may be improved by appropriate training and/or the provision of perceptual cues (e.g. labelling on robot) to aid recognition of movement directions.

2. Standardisation of robot teach pendants is feasible with respect to the motion controls, but this must include standardisation of other factors such as motion reference points and motion labelling.

3. Recommendations for design standardisation cannot be made on the basis of the current data alone. More work is needed to compare control performance using alternative control designs under regulated task conditions.

8.3 Suggestions for further work

1. It has been stated that further work is needed before suitable recommendations for control design(s) can be made. This should involve:
i) Identification of motion reversal conditions for the remaining three degrees of freedom (joints 4,5, 6 and axes RX, RY, RZ) and also for the tool programming mode. This should provide a complete understanding of potential error situations in the robot motion control task.
ii) Examination of the control-motion relationships for alternative control designs and how these are affected by changes in robot status.
iii) Devising control tasks to examine performance under known conditions of motion reversal.
iv) Comparison of control performance in each of these tasks using alternative control designs.
v) Examination of the effect of training and/or perceptual cues on performance.

2. One aspect of the framework produced as part of this work which has not been investigated is path planning. An approach involving mental models identification could be applied to provide information on the possible routes that programmers would normally use for specified tasks and the factors they may take into account. This should provide further understanding of realistic control tasks and the incidence of robot status changes.

3. The theoretical framework and methodologies developed will have relevance to more than robot control. One such application is the area of teleoperation. In many ways it is similar to robot control, since a manipulator arm with similar movement capabilities is being operated. However, feedback of control movement is not available from direct observation of the manipulator due to its remote setting. Potential aspects include:
i) consideration of the consequences of camera position for control-motion compatibility and changes in 'manipulator status', and
ii) evaluation of performance using a camera or graphics display rather than direct observation.

The framework may allow predictions of expected performance and may itself be refined by such applications.

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APPENDICES

I	Industrial robots and their associated teach pendants
II	Control programs used in experimental stages 1 and 2
III	Control programs used for interfacing the experimental teach boxes to the PUMA robot
IV	Statistical results of the experimental analyses
V	PUMA robot movements under different robot status conditions

APPENDIX I

INDUSTRIAL ROBOTS AND THEIR ASSOCIATED TEACH PENDANTS

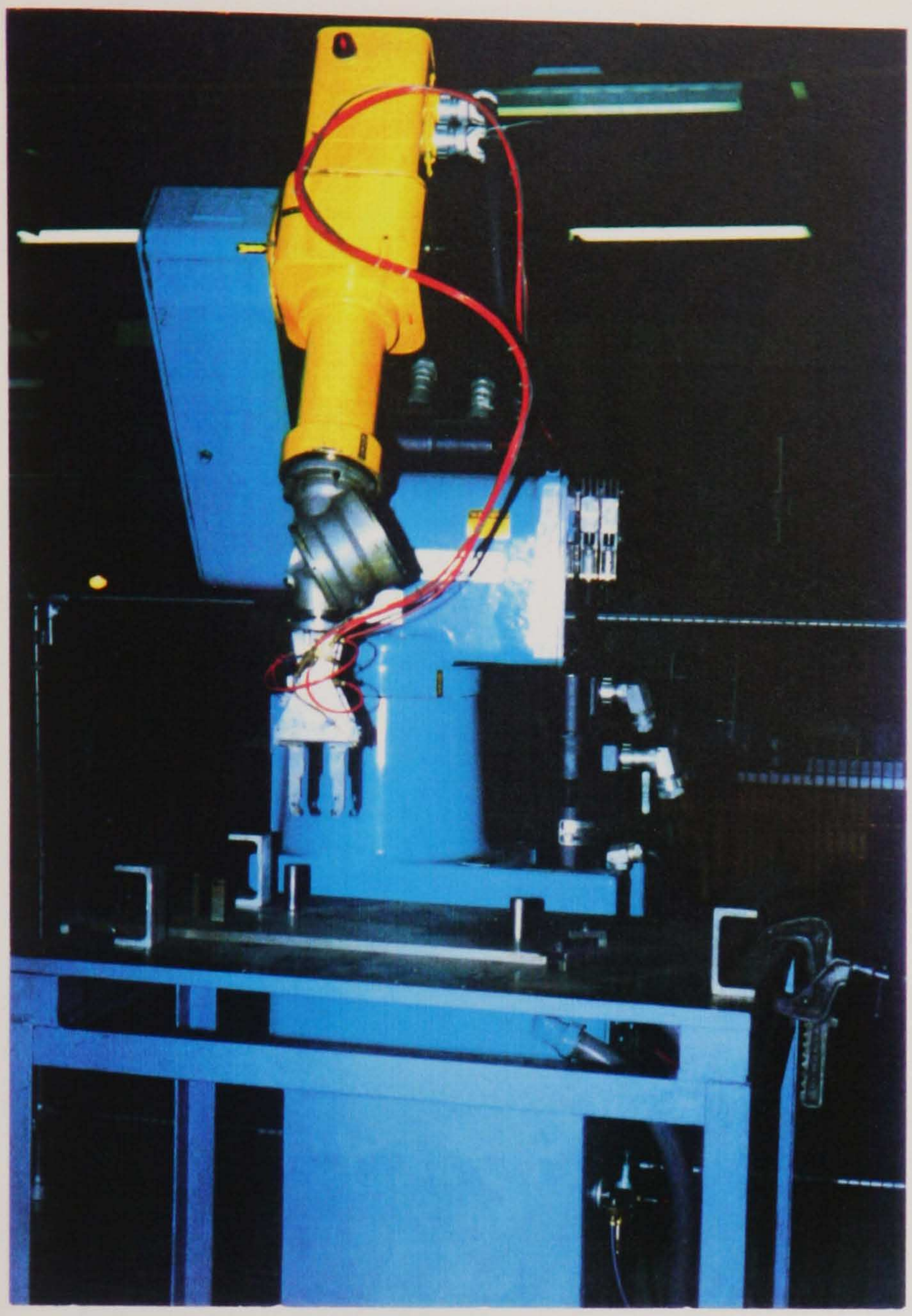
This appendix shows the range of industrial robots available to the author during the course of this work. In addition to those described in the text (the PUMA and ASEA robot systems described in chapter 3), these others were accessed either at Nottingham University, Department of Manufacturing Engineering and Operations Management (Cincinnati system), or at the FORD transit plant in Southampton, UK (Kuka, Lamb Sceptre, British Federal, and Niko systems).

The author does not intend to provide detailed descriptions of each system or its control device as most of this work has been covered by Parsons and Mavor (1986). It is recognised that, although these represent only a part of the total number of robot systems available, they do offer a good illustration of variety in robot systems; particularly in teach pendant design.

The robot systems presented are;

I.1	Cincinnati Milacron T3
I.2	Kuka
I.3	GEC GEM80 Lamb Sceptre
I.4	British Federal
I.5	Niko

Appendix I.1 Cincinnati Milacron T3 robot system



6-axes jointed-spherical robot

No facility for arm-configuration change as joints 2 and 3 have limited travel

One-line display

programming mode selection button

Teach pendant

height: 240mm

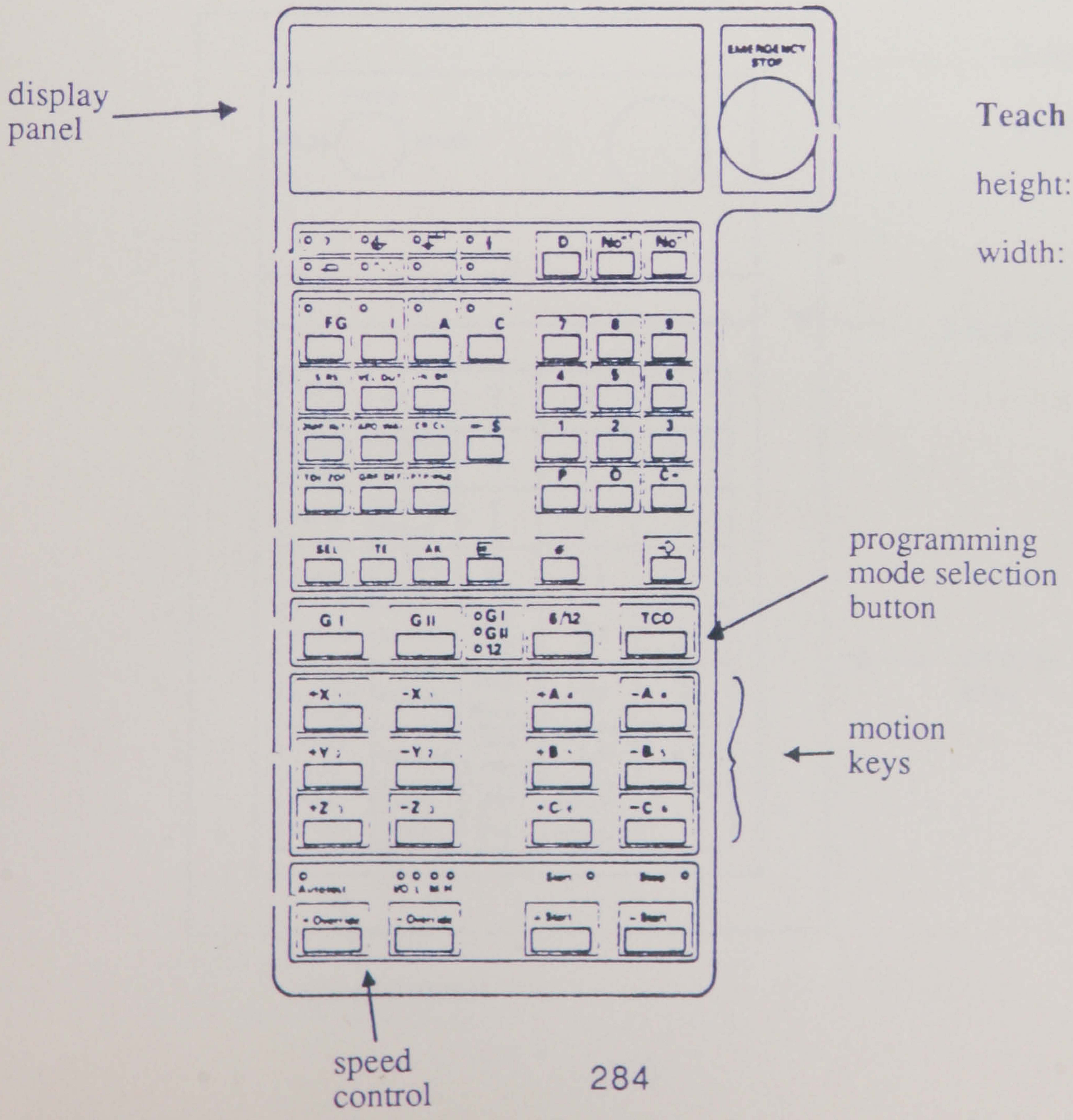
width: 90mm

speed control at side

motion keys

Appendix I.2 Kuka robot system

6-axis jointed-parallelogram robot

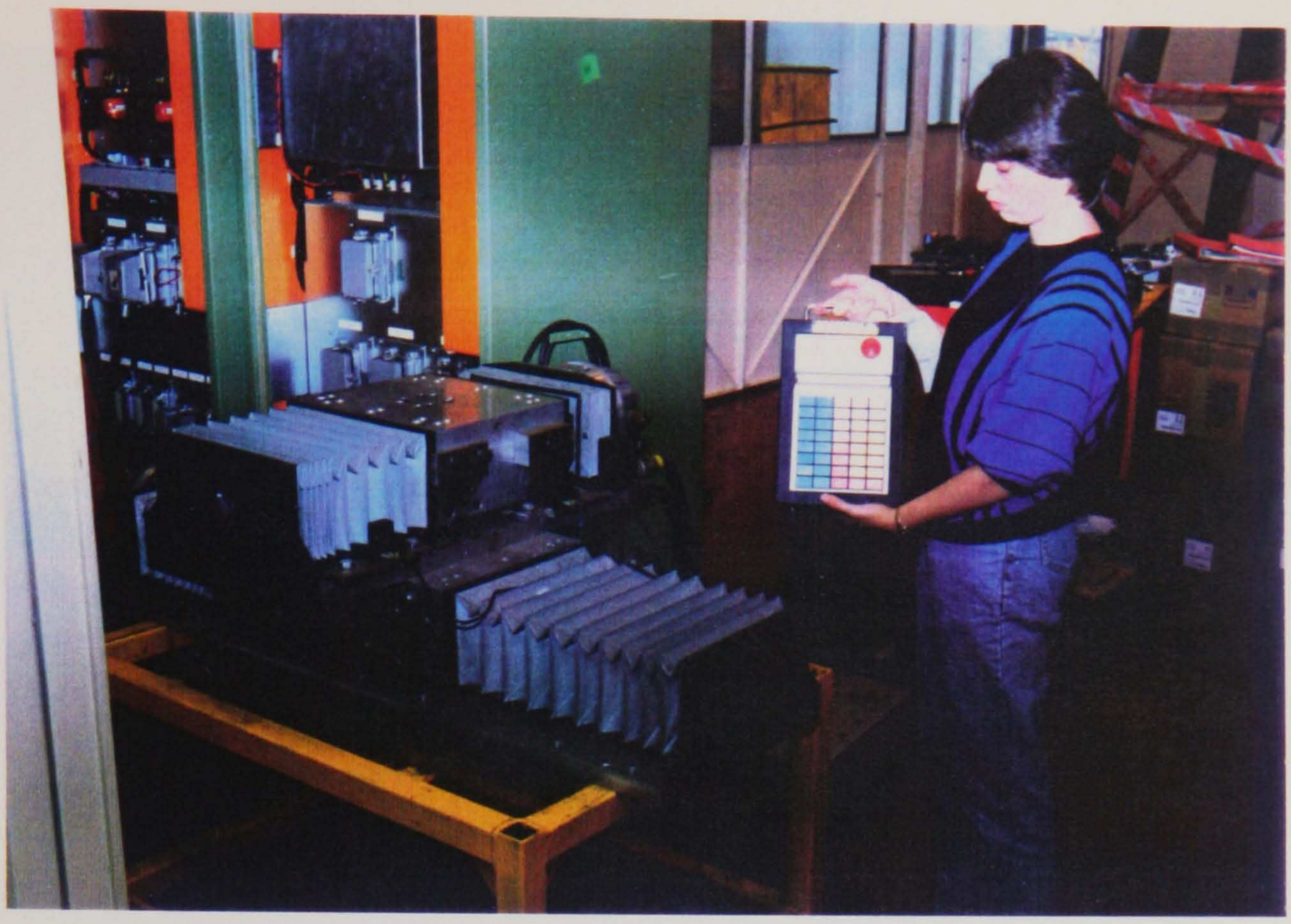


Teach pendant

height: 280mm

width: 120mm

Appendix I.3 GEC GEM80 Lamb Sceptre robot system

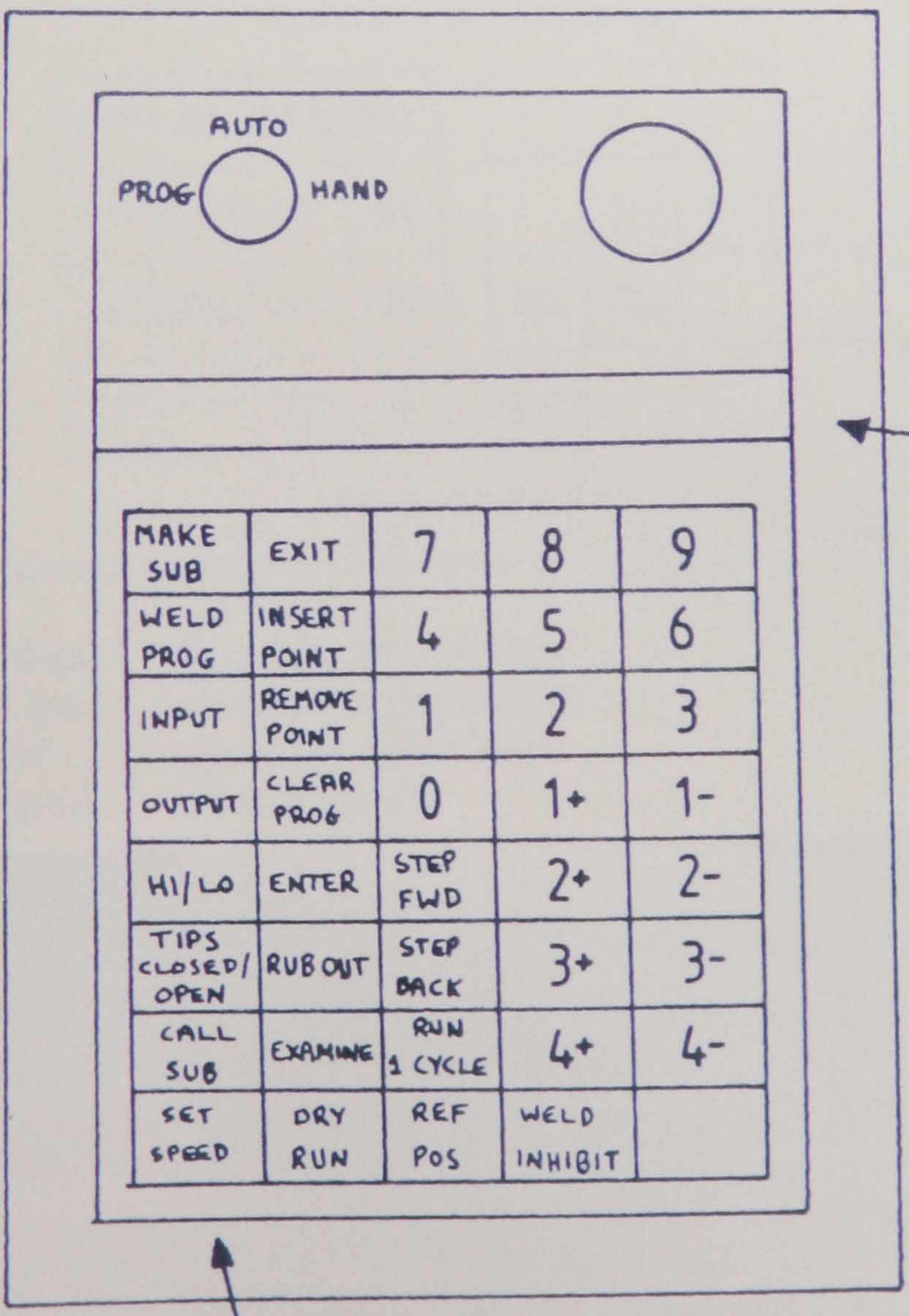


4-axis cartesian-slide robot

Teach pendant

height: 300mm

width: 200mm

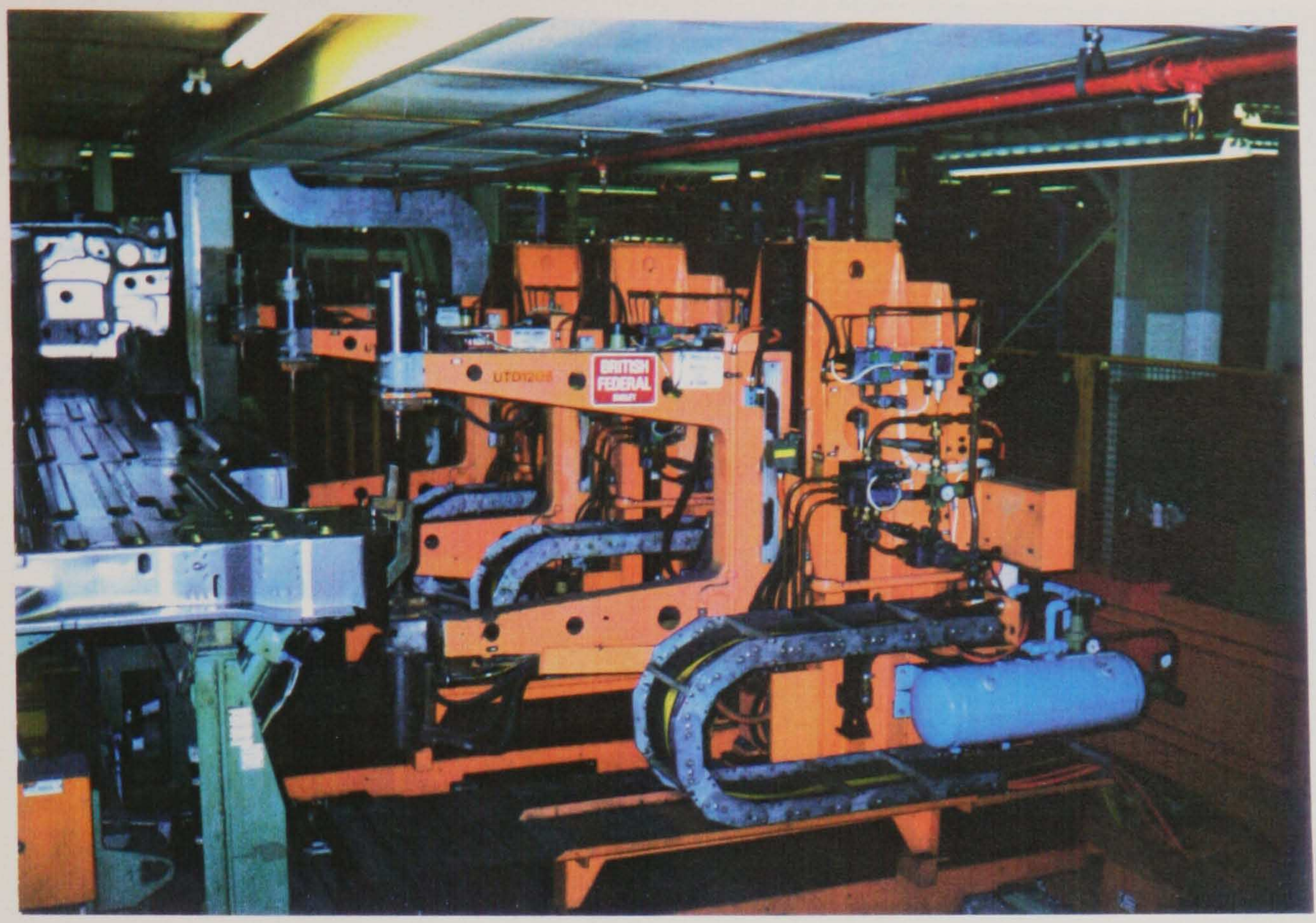


2-line display

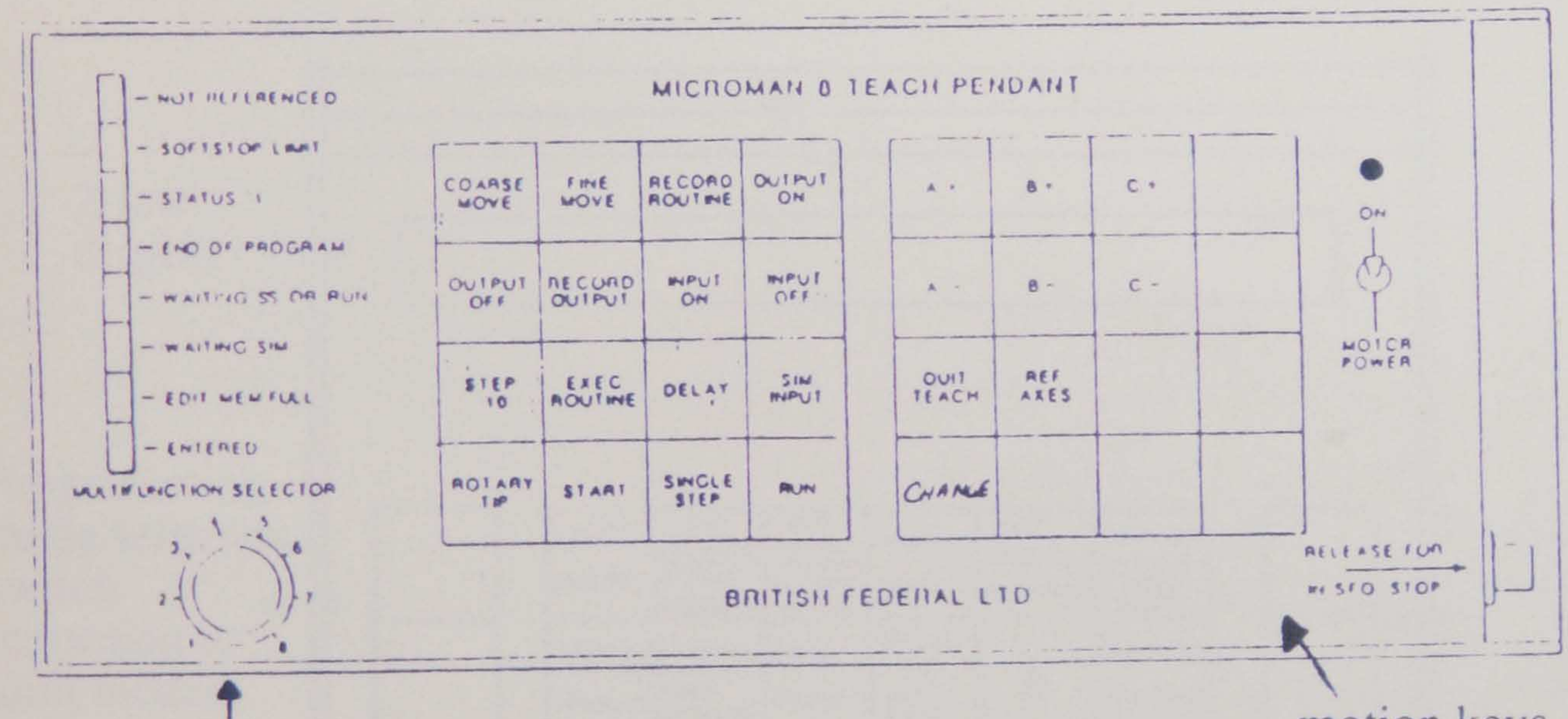
motion keys

speed control

Appendix I.4 British Federal robot system



4-axes cartesian robot



When used with motion keys, the position of the multifunction selector influences motion speed

The function of this selector is dependant upon the other keys used with it

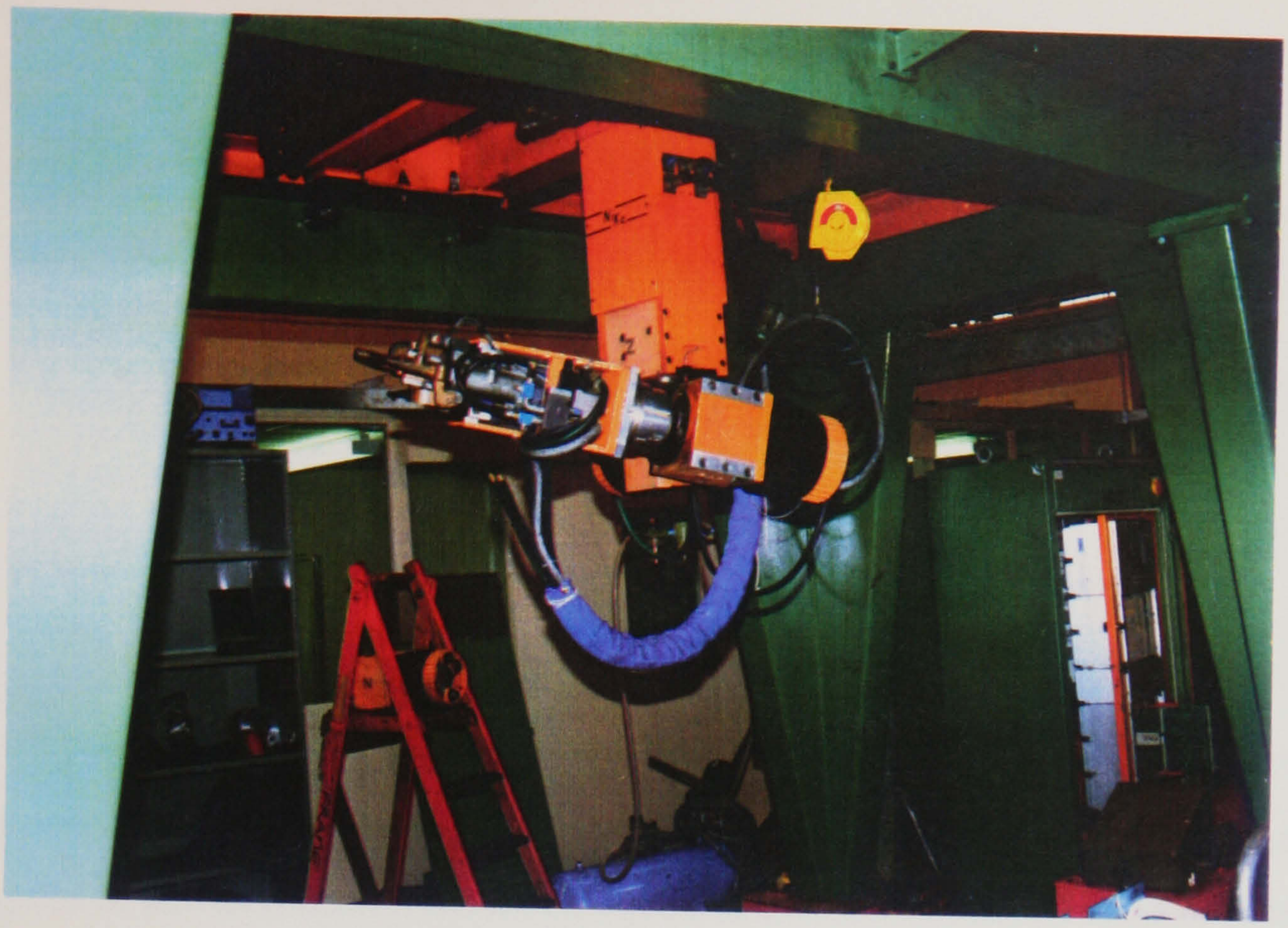
motion keys

Teach pendant

height: 110mm

width: 330mm

Appendix I.5 Niko robot system

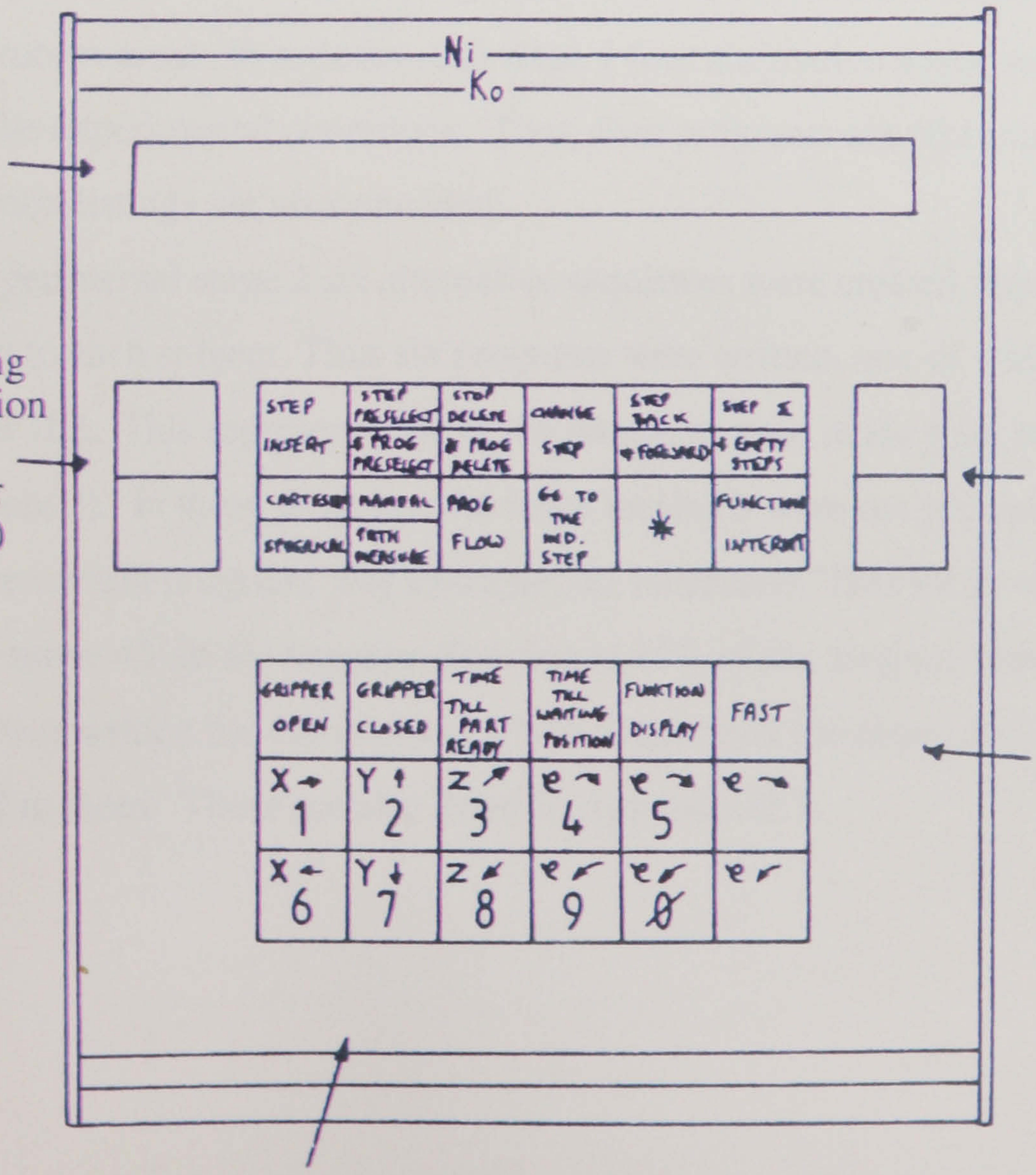


6-axes cartesian robot (gantry mounted)

Teach pendant

height: 250mm

width: 190mm



2-line display

Programming mode selection switch (cartesian or joint modes)

Deadman switches, either side must be held down to enable robot motion

increase speed

motion keys

APPENDIX II

CONTROL PROGRAMS USED IN EXPERIMENTAL STAGES 1 AND 2

This appendix shows some examples of the VAL (I) control programs used in experimenta stages 1 and 2. These govern the movement of the robot to predetermined locations, and the speed of arm movement. Before execution of each movement the robot controller was instructed to wait for external input signal 1. This was provided by the experimenter manually activating an input switch.

For each experiment several programs were written to allow balanced order of the sequenc of robot movements. In experimental stage 1 four alternative sequences were created, one for each of the experimental conditions. Thus, four programs are presented in Appendix II.1. The location listings are also provided.

In experimental stage 2 six alternative sequences were created, four of which were presented to each subject. Thus six programs were written, one of which is presented in Appendix II.2. This represents one of the programs used in the joint mode experiment (experiment 3). In these programs the robot locations were not pre-taught but were instructed within the control program. For example, the command "DRIVE 2, -45.000, 15" instructs joint 2 to move 45° in the negative direction at 15% of the program speed. A main control program was written for each subject which determined the sequence movement programs presented to them. These are also listed in Appendix II.2.

Appendix II.1 Program listings for experimental stage 1

```
.PROGRAM PROG
        SPEED 80.00
        LEFTY
        MOVE C1
        DELAY 1.00
        WAIT 1
        SPEED 40.00 ALWAYS
        MOVET D1, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D2, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D3, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D4, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D5, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D6, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D7, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D8, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D9, 0.00
        DELAY 1.00
        WAIT 1
        MOVET D10, 0.00
        DELAY 1.00
        WAIT 1
        MOVE D11
        DELAY 1.00
        WAIT 1
        MOVET D12, 0.00
        DELAY 1.00
        WAIT 1
        SPEED 80.00
        READY
        RETURN 0
.END
```

```
.PROGRAM PROG1
        SPEED 80.00
        RIGHTY
        MOVE C1
        DELAY 1.00
        WAIT 1
        SPEED 40.00 ALWAY
        MOVET E1, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E2, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E3, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E4, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E5, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E6, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E7, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E8, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E9, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E10, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E11, 0.00
        DELAY 1.00
        WAIT 1
        MOVET E12, 0.00
        DELAY 1.00
        WAIT 1
        SPEED 80.00
        READY
        RETURN 0
.END
```

```
.PROGRAM PROG2
        SPEED 80.00
        RIGHTY
        MOVE C2
        DELAY 1.00
        WAIT 1
        SPEED 40.00 ALWAYS
        MOVET F1, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F2, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F3, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F4, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F5, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F6, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F7, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F8, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F9, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F10, 0.00
        DELAY 1.00
        WAIT 1
        MOVET F11, 0.00
        DELAY 1.00
        WAIT 1
        MOVE F12
        DELAY 1.00
        WAIT 1
        SPEED 80.00
        READY
        RETURN 0
.END
```

```
.PROGRAM PROG3
        SPEED 80.00
        LEFTY
        MOVE C2
        DELAY 1.00
        WAIT 1
        SPEED 40.00 ALWAYS
        MOVET G1, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G2, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G3, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G4, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G5, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G6, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G7, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G8, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G9, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G10, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G11, 0.00
        DELAY 1.00
        WAIT 1
        MOVET G12, 0.00
        DELAY 1.00
        WAIT 1
        SPEED 80.00
        READY
        RETURN 0
.END
```

	X/JT1	Y/JT2	Z/JT3	O/JT4	A/JT5	T/JT6
C1	432.66	475.97	-98.94	75.894	86.660	129.606
D1	410.72	460.84	205.91	119.564	59.771	173.897
D2	617.16	13.47	205.91	72.521	59.771	173.875
D3	632.22	10.13	554.63	74.883	16.996	177.418
D4	620.06	11.66	533.13	72.559	42.314	176.232
D5	444.34	432.56	533.13	115.708	42.314	176.237
D6	444.25	432.53	533.16	115.708	42.308	-96.751
D7	451.19	382.88	584.94	54.476	-14.326	-165.454
D8	591.44	465.97	354.00	57.667	-5.795	176.479
D9	568.31	506.63	298.66	113.956	61.974	-99.080
D10	454.47	439.13	-1.72	-46.527	75.668	99.261
D11	454.44	439.06	-1.81	-46.571	75.668	19.243
D12	492.28	464.16	6.22	119.064	55.717	173.452

Locations used in "PROG1"

	X/JT1	Y/JT2	Z/JT3	O/JT4	A/JT5	T/JT6
C1	432.66	475.97	-98.94	75.894	86.660	129.606
E1	406.38	427.94	274.41	145.882	54.338	-159.439
E2	587.81	51.97	274.47	104.453	54.333	-159.434
E3	578.63	48.63	586.53	106.633	16.216	-155.858
E4	556.47	46.13	648.28	113.654	-54.943	-158.736
E5	356.94	429.34	648.31	159.175	-54.948	-158.725
E6	356.97	429.34	648.31	159.175	-54.937	-78.151
E7	341.09	450.91	623.84	-175.182	-22.555	-178.962
E8	428.16	642.13	336.41	-177.605	-.698	-167.168
E9	449.72	630.53	364.13	156.682	-30.355	-73.570
E10	431.69	590.94	127.31	156.528	-1.511	-72.999
E11	431.69	590.94	127.34	156.528	-1.522	-179.797
E12	414.84	547.31	70.50	145.047	80.090	170.596

Locations used in "PROG2"

	X/JT1	Y/JT2	Z/JT3	O/JT4	A/JT5	T/JT6
C1	432.66	475.97	-98.94	75.894	86.660	129.606
F1	-418.88	433.22	192.97	-123.041	56.058	-69.164
F2	-210.34	564.69	192.97	-146.651	56.058	-69.164
F3	-233.44	597.91	494.09	-146.047	19.265	-68.231
F4	-225.06	583.19	555.69	-143.992	-49.911	-68.890
F5	-622.38	59.16	555.72	-80.530	-49.916	-68.906
F6	-622.38	59.16	555.63	-80.530	-49.905	-1.379
F7	-627.56	28.47	524.47	-48.181	-12.112	-102.222
F8	-791.03	4.63	209.53	-48.538	9.185	-88.347
F9	-797.63	20.56	238.69	-66.649	-21.022	-27.664
F10	-691.53	36.03	-6.72	-67.429	10.344	-19.528
F11	-691.53	36.03	-6.78	-67.429	10.349	-176.495
F12	-683.88	49.84	-31.69	-80.305	38.430	178.022

Locations used in "PROG3"

	X/JT1	Y/JT2	Z/JT3	O/JT4	A/JT5	T/JT6
C1	432.66	475.97	-98.94	75.894	86.660	129.606
G1	-425.09	418.44	210.91	-142.998	54.800	-90.181
G2	-49.41	594.47	210.91	176.303	54.794	-90.176
G3	-44.59	621.34	529.72	173.743	16.062	-94.340
G4	-50.56	603.16	501.69	-179.912	50.812	-90.687
G5	-517.19	314.47	501.69	-126.002	50.812	-90.687
G6	-517.19	314.47	501.69	-126.002	50.812	12.437
G7	-465.31	344.16	553.41	155.451	-8.300	-74.674
G8	-587.75	471.75	270.63	156.890	1.027	-97.092
G9	-618.75	430.81	217.06	-140.246	75.597	-2.587
G10	-555.44	364.81	28.28	48.593	77.745	-173.974
G11	-555.44	364.81	28.34	48.604	77.745	98.267
G12	-589.06	398.84	39.97	-136.620	50.312	-87.369

Appendix II.2 An example program listing used in experiment 3

```
.PROGRAM SMA
   1.       SPEED 20.00 ALWAYS
   2.       DELAY 0.20
   3.       WAIT 1
   4.       DRIVE 2, -45.000, 15.00
   5.       HERE £J1
   6.       DELAY 0.20
   7.       WAIT 1
   8.       DRIVE 3, -49.999, 15.00
   9.       HERE £J2
  10.       DELAY 0.20
  11.       WAIT 1
  12.       DRIVE 2, 74.998, 15.00
  13.       HERE £J3
  14.       DELAY 0.20
  15.       WAIT 1
  16.       DRIVE 1, 45.000, 15.00
  17.       HERE £J4
  18.       DELAY 0.20
  19.       WAIT 1
  20.       DRIVE 1, -69.999, 15.00
  21.       HERE £J5
  22.       DELAY 0.20
  23.       WAIT 1
  24.       DRIVE 3, 94.999, 15.00
  25.       HERE £J6
  26.       DELAY 0.20
  27.       WAIT 1
  28.       READY
  29.       RETURN 0
.END
```

```
.LISTL
             X/JT1     Y/JT2     Z/JT3     O/JT4     A/JT5     T/JT6
£J1          0.005  -135.000    90.000     0.000     0.005      0.00
£J2          0.005  -135.005    40.040     0.000     0.005      0.00
£J3          0.005   -60.029    40.007     0.005     0.005      0.00
£J4         44.989   -60.002    40.001     0.005     0.005      0.00
£J5        -24.988   -60.002    40.007     0.005     0.005      0.00
£J6        -24.988   -60.002   134.962     0.005     0.005      0.00
```

Control programs governing the sequence of movement programs presented to each subject.

```
.PROGRAM S1
   1.        GOSUB SMC
   2.        GOSUB SMD
   3.        GOSUB SMA
   4.        GOSUB SMB
   5.        READY
.END
```

```
.PROGRAM S2
   1.        GOSUB SMC
   2.        GOSUB SMB
   3.        GOSUB SME
   4.        GOSUB SMD
   5.        READY
.END
```

```
.PROGRAM S3
   1.        GOSUB SMF
   2.        GOSUB SME
   3.        GOSUB SMD
   4.        GOSUB SMC
   5.        READY
.END
```

```
.PROGRAM S4
   1.        GOSUB SMD
   2.        GOSUB SME
   3.        GOSUB SMF
   4.        GOSUB SMA
   5.        READY
.END
```

```
.PROGRAM S5
   1.        GOSUB SMA
   2.        GOSUB SMB
   3.        GOSUB SME
   4.        GOSUB SMF
   5.        READY
.END
```

```
.PROGRAM S6
   1.        GOSUB SMA
   2.        GOSUB SMF
   3.        GOSUB SMC
   4.        GOSUB SMB
   5.        READY
.END
```

```
.PROGRAM S7
   1.        GOSUB SMD
   2.        GOSUB SMC
   3.        GOSUB SMB
   4.        GOSUB SMA
   5.        READY
.END
```

```
.PROGRAM S8
   1.        GOSUB SMB
   2.        GOSUB SMC
   3.        GOSUB SMD
   4.        GOSUB SME
   5.        READY
.END
```

```
.PROGRAM S9
   1.        GOSUB SME
   2.        GOSUB SMF
   3.        GOSUB SMC
   4.        GOSUB SMD
   5.        READY
.END
```

```
.PROGRAM S10
   1.        GOSUB SME
   2.        GOSUB SMD
   3.        GOSUB SMA
   4.        GOSUB SMF
   5.        READY
.END
```

```
.PROGRAM S11
   1.        GOSUB SMB
   2.        GOSUB SMA
   3.        GOSUB SMF
   4.        GOSUB SME
   5.        READY
.END
```

```
.PROGRAM S12
   1.        GOSUB SMF
   2.        GOSUB SMA
   3.        GOSUB SMB
   4.        GOSUB SMC
   5.        READY
.END
```

APPENDIX III

CONTROL PROGRAMS USED FOR INTERFACING THE EXPERIMENTAL TEACH BOXES TO THE PUMA ROBOT

This appendix shows the VAL (I) control programs used to interface the experimental teach boxes to the PUMA robot. The controls on the teach boxes were linked to the robot controller via the external input port. In the case of the toggle-switch box this was a direct link. The joystick control, however, was linked via a BBC computer which converted the control signal from digital to analogue. Each control initiated a separate input signal to the robot controller.

The control programs were created to continuously search for an initiated input signal. when found, the appropriate control movement was instructed. This activated robot movemen of the relevant joint/axis by a small amount in either the positive or negative direction. Continuous movement would result from repeated activation of the input signal, and the movement would stop when the input signal was no longer activated.

Two programs are listed in this appendix; one which was used to control movements in joint mode, and the other which was used to control movements in world mode.

Appendix III. Program listings of the programs used to interface the experimental teach boxes with the PUMA robot

Joint mode

```
.PROGRAM ONEJOINT
       SPEED 100.00 ALWAYS
     1 IFSIG 2, 3, 4, 5 THEN 25
     2 IFSIG 6, 7, 8, 9 THEN 25
     3 IFSIG 10, 11, 12, 13 THEN 25
    10 IFSIG 10, , ,  THEN 30
    11 IFSIG 11, , ,  THEN 31
    12 IFSIG 6, , ,  THEN 32
    13 IFSIG 7, , ,  THEN 33
    14 IFSIG 2, , ,  THEN 34
    15 IFSIG 3, , ,  THEN 35
       DELAY 0.01
       GOTO 1
       DELAY 0.01
    30 DRIVE 1, 0.500, 100.00
       GOTO 10
    31 DRIVE 1, -.500, 100.00
       GOTO 11
    32 DRIVE 2, 0.500, 100.00
       GOTO 12
    33 DRIVE 2, -.500, 100.00
       GOTO 13
    34 DRIVE 3, 0.500, 100.00
       GOTO 14
    35 DRIVE 3, -.500, 100.00
       GOTO 15
       RETURN 0
.END
```

World mode

```
.PROGRAM ONEWORLD
       SPEED 100.00 ALWAYS
       TOOL HAND
     1 IFSIG 2, 3, 4, 5 THEN
     2 IFSIG 6, 7, 8, 9 THEN
     3 IFSIG 10, 11, 12, 13
    10 IFSIG 10, , ,  THEN 3
    11 IFSIG 11, , ,  THEN 3
    12 IFSIG 6, , ,  THEN 32
    13 IFSIG 7, , ,  THEN 33
    14 IFSIG 2, , ,  THEN 34
    15 IFSIG 3, , ,  THEN 35
       DELAY 0.01
       GOTO 1
    25 DELAY 0.01
       GOTO 1
    30 DRAW 4.00, 0.00, 0.00
       GOTO 10
    31 DRAW -4.00, 0.00, 0.0
       GOTO 11
    32 DRAW 0.00, 4.00, 0.00
       GOTO 12
    33 DRAW 0.00, -4.00, 0.0
       GOTO 13
    34 DRAW 0.00, 0.00, 4.00
       GOTO 14
    35 DRAW 0.00, 0.00, -4.0
       GOTO 15
       RETURN 0
.END
```

APPENDIX IV

STATISTICAL RESULTS OF THE EXPERIMENTAL ANALYSES

IV.1 Statistical results for experiment 2: Analysis 1. Joint identification
IV.2 Statistical results for experiment 2: Analysis 2. Direction errors
IV.3 Statistical results for experiment 3: Analysis 1. Total errors
IV.4 Statistical results for experiment 4: Analysis 1. Total errors
IV.5 Statistical results for experiment 4: Analysis 2. Direction errors
IV.6 Statistical results for experiment 4: Analysis 3. Control errors
IV.7 Statistical results for re-interpretation of experiment 2: Analysis 2. Direction-of-movement
IV.8 Statistical results for experiment 5: Analysis 1. Total errors
IV.9 Statistical results for experiment 5: Analysis 2. Direction errors
IV.10 Statistical results for experiment 5: Analysis 3. Control errors
IV.11 Statistical results for experiment 5: Analysis 4. Response times
IV.12 Statistical results for experiment 6: Analysis 1. Total errors
IV.13 Statistical results for experiment 6: Analysis 2. Direction errors
IV.14 Statistical results for experiment 6: Analysis 3. Control errors
IV.15 Statistical results for experiment 6: Analysis 4. Task completion times

Appendix IV.1 Statistical results for experiment 2: Analysis 1. Joint identification.

i. Raw data for joint identification errors.

	Group	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6
1	words	0	0	0	7	5	3
2	words	0	0	0	0	2	0
3	words	0	0	1	1	0	0
4	words	0	0	0	0	0	0
5	words	0	0	0	0	0	0
6	words	0	0	0	2	5	8
7	words	0	0	1	1	8	8
8	words	0	0	0	8	0	1
9	words	0	0	0	0	1	0
10	words	0	0	0	4	1	6
11	numbers	0	0	0	0	1	0
12	numbers	0	0	0	2	1	0
13	numbers	0	1	2	0	1	0
14	numbers	0	0	0	2	2	2
15	numbers	0	0	0	0	4	1
16	numbers	1	1	7	0	6	3
17	numbers	0	0	0	0	3	0
18	numbers	0	0	0	0	0	0
19	numbers	0	0	0	0	0	0
20	numbers	0	0	1	1	0	0

ii. ANOVA summary table (transformed data).

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
G	1	.331	.331	.433	.5188	
Error	18	13.760	.764			
J	5	9.911	1.982	7.440	.0000	
GJ	5	2.974	.595	2.233	.0577	
Error	90	23.977	.266			.55

iii. Tukey test for comparison of mean errors on each joint (transformed data).

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D	E	F
A. Joint 1	X	-	-	s	s	s
B. Joint 2	-	X	-	s	s	s
C. Joint 3	-	-	X	-	-	s
D. Joint 4	-	-	-	X	-	-
E. Joint 6	-	-	-	-	X	-
F. Joint 5	s	s	-	-	-	X

iv. Simple main effects of group-joint interaction (transformed data).

Effect	MSn	DFn	DFe	MSe	F	p
G at Joint 1	.024	1	18	.024	1.000	.331
G at Joint 2	.096	1	18	.043	2.250	.151
G at Joint 3	.309	1	18	.293	1.052	.319
G at Joint 4	1.502	1	18	.498	3.017	.099
G at Joint 5	.001	1	18	.608	.002	.967
G at Joint 6	1.374	1	18	.631	2.178	.157
J at words	1.893	5	90	.266	7.107	.000
J at numbers	.684	5	90	.266	2.566	.032

v. Tukey test for comparison of means within each terminology group.

Words group

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D	E	F
A. Joint 1	X	-	-	s	s	s
B. Joint 2	-	X	-	s	s	s
C. Joint 3	-	-	X	s	s	s
D. Joint 5	-	-	-	X	-	-
E. Joint 4	-	-	-	-	X	-
F. Joint 6	-	-	-	-	-	X

Numbers group

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D	E	F
A. Joint 1	X	-	-	-	-	s
B. Joint 2	-	X	-	-	-	s
C. Joint 4	-	-	X	-	-	-
D. Joint 6	-	-	-	X	-	-
E. Joint 3	-	-	-	-	X	-
F. Joint 5	s	-	-	-	-	X

Appendix IV.2 Statistical results for experiment 2: Analysis 2. Direction of movement.

i. Raw data for direction of movement errors.

	Group	Config A	Config B	Config C	Config D
1	1	1	7	3	6
2	1	2	7	4	8
3	1	2	2	0	0
4	1	1	6	1	3
5	1	1	4	4	8
6	1	3	10	9	2
7	1	6	6	0	5
8	1	1	1	1	4
9	1	2	2	0	4
10	1	1	6	0	6
11	2	11	4	2	10
12	2	8	4	3	9
13	2	8	3	1	8
14	2	9	0	3	8
15	2	9	4	2	9
16	2	8	2	3	10
17	2	10	3	3	11
18	2	10	2	2	9
19	2	10	7	2	11
20	2	10	4	3	9

ii. ANOVA summary table.

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
G	1	137.813	137.813	21.510	.0002	
Error	18	115.325	6.407			
C	3	243.438	81.146	26.306	.0000	
GC	3	260.238	86.746	28.121	.0000	
Error	54	166.575	3.085			.94

ii. Simple main effects of group-configuration interaction.

Effect	MSn	DFn	DFe	MSe	F	p
G at A	.200	1	18	4.444	.045	.834
G at B	16.200	1	18	5.611	2.887	.107
G at C	266.450	1	18	1.783	149.411	.000
G at D	115.200	1	18	3.822	30.140	.000
C at ROTATION	25.692	3	54	3.085	8.329	.000
C at LINEAR	142.200	3	54	3.085	46.098	.000

iii. Tukey test for comparison of mean errors within each terminology group.

Rotation terminology

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. C	X	-	s	s
B. A	-	X	s	s
C. D	-	-	X	-
D. B	-	-	-	X

Linear movement terminology

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. A	X	-	s	s
B. B	-	X	s	s
C. C	s	s	X	-
D. D	s	s	-	X

Appendix IV.3 Statistical results for experiment 3: Analysis 1. Total errors.

i. Raw data for total error scores.

	Joy Front	Joy left	Joy right	Joy back	Togg Front	Togg left	Togg right	Togg back
1	6	5	6	6	6	6	6	6
2	3	2	4	3	2	1	2	2
3	2	2	2	2	2	2	2	2
4	2	2	2	2	4	2	2	2
5	6	6	4	2	3	4	3	2
6	4	2	6	5	5	4	4	6
7	4	2	2	0	2	2	2	2
8	6	2	6	2	6	2	6	2
9	4	5	4	4	4	4	4	3
10	6	6	6	6	2	5	4	6
11	6	2	2	2	6	2	5	2
12	6	5	4	6	6	6	6	6

ii. ANOVA summary table.

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
Subjects	11	168.115	15.283			
p	1	.844	.844	.553	.4727	
Error	11	16.781	1.526			1.00
o	3	14.448	4.816	2.225	.1037	
Error	33	71.427	2.164			.69
po	3	1.448	.483	.743	.5339	
Error	33	21.427	.649			.76

Appendix IV.4 Statistical results for experiment 4: Analysis 1. Total errors.

i. Raw data for total error scores.

	Joy Front	Joy left	Joy right	Joy back	Togg front	Togg left	Togg right	Togg back
1	0	0	0	0	0	0	0	0
2	5	2	2	4	6	2	5	6
3	4	2	2	4	4	0	4	4
4	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	1
6	4	4	4	4	4	0	1	2
7	4	0	1	1	3	1	2	0
8	0	0	0	0	0	0	0	0
9	0	0	3	0	0	0	0	0
10	2	0	0	0	0	0	0	0
11	4	4	4	4	4	4	4	4
12	3	2	3	2	2	2	3	2

ii. ANOVA summary table (transformed data).

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
Subjects	11	38.082	3.462			
P	1	.138	.138	.810	.3873	
Error	11	1.878	.171			1.00
0	3	1.983	.661	5.079	.0053	
Error	33	4.295	.130			.84
P0	3	.076	.025	.242	.8665	
Error	33	3.469	.105			.80

iii. Tukey test for comparison of mean errors at each orientation (transformed data).

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. LEFT	X	-	-	s
B. BACK	-	X	-	-
C. RIGHT	-	-	X	-
D. FRONT	s	-	-	X

Appendix IV.5 Statistical results for experiment 4: Analysis 2. Direction errors.

i. Raw data for direction errors.

	Joy Front	Joy left	Joy right	Joy back	Togg Front	Togg left	Togg right	Togg back
1	0	0	0	0	0	0	0	0
2	1	2	2	0	2	2	5	2
3	0	2	2	0	0	0	4	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	1	2
7	3	0	1	0	2	1	2	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	2	0	0	0	0	0	0	0
11	2	4	4	4	4	4	4	4
12	2	2	2	2	2	2	3	2

ii. ANOVA summary table (transformed data).

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
Subjects	11	25.232	2.294			
p	1	.159	.159	1.506	.2454	
Error	11	1.165	.106			1.00
o	3	.841	.280	1.735	.1790	
Error	33	5.331	.162			.72
po	3	.337	.112	1.873	.1534	
Error	33	1.981	.060			.77

Appendix IV.6 Statistical results for experiment 4: Analysis 3. Control errors.

i. Raw data for control errors.

	Joystick front	Joystick left	Joystick right	Joystick back	Toggle front	Toggle left	Toggle right	Toggle back
1	0	0	0	0	0	0	0	0
2	4	0	0	4	4	1	0	4
3	4	0	0	4	4	0	0	4
4	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	1
6	4	4	4	4	4	0	0	0
7	0	0	0	1	1	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	2	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	2	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0

ii. ANOVA summary table (transformed data).

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
Subjects	11	12.722	1.157			
P	1	.331	.331	1.123	.3120	
Error	11	3.245	.295			1.00
0	3	3.347	1.116	4.273	.0118	
Error	33	8.616	.261			.43
P0	3	.124	.041	.482	.6973	
Error	33	2.834	.086			.60

iii. Tukey test for comparison of mean errors at each orientation (transformed data).

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. LEFT	X	-	-	s
B. RIGHT	-	X	-	s
C. BACK	-	-	X	-
D. FRONT	-	-	-	X

Appendix IV.7 Statistical results for re-interpretation of experiment 2: Analysis 2. Direction of movement.

i. Raw data for direction of movement errors.

	Column 1	Column 2	Column 3	Column 4	Column 5
1	1	3	7	1	6
2	1	4	7	2	8
3	1	4	4	1	8
4	1	9	10	3	2
5	1	0	6	6	5
6	1	0	6	1	6
7	2	2	4	11	10
8	2	3	4	8	9
9	2	1	3	8	8
10	2	3	0	9	8
11	2	2	4	9	9
12	2	3	2	8	10
13	2	3	3	10	11
14	2	2	2	10	9
15	2	2	7	10	11
16	2	3	4	10	9

ii. ANOVA summary table.

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
G	1	36.426	36.426	12.497	.0033	
Error	14	40.808	2.915			
C	3	174.803	58.268	18.397	.0000	
GC	3	239.053	79.684	25.159	.0000	
Error	42	133.025	3.167			.87

iii. Simple main effects of group-configuration interaction.

Effect	MSn	DFn	DFe	MSe	F	p
G at A	3.267	1	14	4.267	.766	.396
G at B	42.504	1	14	3.531	12.038	.004
G at C	182.004	1	14	2.102	86.570	.000
G at D	47.704	1	14	2.517	18.955	.001
C at ROTATION	25.042	3	42	3.167	7.906	.000
C at LINEAR	142.200	3	42	3.167	44.897	.000

iv. Tukey test for comparison of mean errors within each terminology group.

Rotation terminology

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. C	X	-	-	s
B. A	-	X	-	-
C. D	-	-	X	-
D. B	-	-	-	X

Linear movement terminology

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. C	X	-	s	s
B. A	-	X	-	s
C. D	-	-	X	-
D. B	-	-	-	X

Appendix IV.8 Statistical results for experiment 5: Analysis 1. Total errors.

i. Raw data for total error scores.

	Subject Nº	Group	Joystick a	Joystick b	Joystick c	joystick d	Toggle a	Toggle b	Toggle c	Toggle d
1	3	1	0	2	1	4	0	1	2	2
2	5 *	1	6	5	7	9	2	0	2	3
3	6	1	5	3	3	2	4	0	3	4
4	8	1	2	3	4	3	2	1	5	2
5	9 *	1	6	5	8	7	5	5	10	8
6	12 *	1	4	2	7	6	5	1	9	6
7	13	1	4	2	6	5	5	3	5	5
8	1	2	0	1	0	2	0	0	1	3
9	2	2	3	6	4	3	1	2	4	2
10	4	2	1	3	2	2	0	0	0	1
11	7	2	0	2	0	2	3	2	0	0
12	10	2	2	2	6	5	5	3	5	5
13	11	2	2	3	3	1	2	2	2	1
14	14	2	5	2	5	3	0	2	5	4
15	15	2	5	4	4	10	2	2	2	4

* Did not use cues on the robot arm for direction reference (see section 6.3.1.3, C. Subject preferences).

ii. ANOVA summary table.

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
G	1	65.215	65.215	3.480	.0849	
Error	13	243.652	18.742			
P	1	19.717	19.717	3.675	.0775	
GP	1	.117	.117	.022	.8850	
Error	13	69.750	5.365			1.00
C	3	58.096	19.365	7.163	.0006	
GC	3	21.763	7.254	2.683	.0599	
Error	39	105.438	2.704			.90
PC	3	4.982	1.661	1.349	.2726	
GPC	3	.849	.283	.230	.8751	
Error	39	48.018	1.231			.78

iii. Tukey test for comparison of mean errors at each robot arm-configuration.

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. B	X	-	s	s
B. A	-	X	-	s
C. D	s	-	X	-
D. C	s	-	-	X

iv. Newman-Keuls test for comparison of mean errors at each robot arm-configuration.

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. B	X	-	s	s
B. A	-	X	s	s
C. D	s	-	X	-
D. C	s	-	-	X

v. Simple main effects of group-configuration interaction.

Effect	MSn	DFn	DFe	MSe	F	p
G at A	19.934	1	13	5.067	3.934	.069
G at B	.086	1	13	2.593	.033	.859
G at C	45.015	1	13	11.050	4.074	.065
G at D	21.943	1	13	8.143	2.695	.125
C Observer-based	10.938	3	39	2.704	4.046	.013
C at Robot-based	1.760	3	39	2.704	.651	.587

vi. Tukey test for comparison of mean errors within the observer-based group.

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. B	X	-	s	s
B. A	-	X	-	-
C. D	s	-	X	-
D. C	s	-	-	X

Appendix IV.9 Statistical results for experiment 5: Analysis 2. Direction errors.

i. Raw data for direction errors.

	Group	Joystick A	Joystick B	Joystick C	Joystick D	Toggle A	Toggle B	Toggle C	Toggle D
1	1	0	2	1	4	0	1	2	2
2	1	6	4	7	8	2	0	2	3
3	1	5	2	2	2	4	0	3	3
4	1	2	3	3	2	2	1	5	2
5	1	6	5	8	4	10	8	5	5
6	1	3	2	7	5	5	1	9	6
7	1	3	1	6	4	4	3	5	5
8	2	0	1	0	2	0	0	1	2
9	2	3	6	4	3	1	2	4	2
10	2	0	3	2	2	0	0	0	0
11	2	0	2	0	1	3	2	0	0
12	2	2	1	6	5	5	2	5	5
13	2	2	3	3	1	2	2	2	1
14	2	4	1	5	3	0	2	3	4
15	2	4	4	4	10	2	1	1	3

ii. ANOVA summary table.

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
G	1	59.438	59.438	3.562	.0816	
Error	13	216.929	16.687			
P	1	11.834	11.834	2.015	.1793	
GP	1	2.834	2.834	.482	.4996	
Error	13	76.366	5.874			1.00
C	3	54.219	18.073	6.013	.0018	
GC	3	21.152	7.051	2.346	.0877	
Error	39	117.214	3.005			.90
PC	3	3.583	1.194	.934	.4336	
GPC	3	3.249	1.083	.847	.4767	
Error	39	49.884	1.279			.79

iii. Tukey test for comparison of mean errors at each robot arm-configuration.

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. B	X	-	s	s
B. A	-	X	-	-
C. D	-	-	X	-
D. C	s	-	-	X

Appendix IV.10 Statistical results for experiment 5: Analysis 3. Control errors.

i. Raw data for control errors.

	Group	Joystick A	Joystick B	Joystick C	Joystick D	Toggle A	Toggle B	Toggle C	Toggle D
1	1	0	0	0	0	0	0	0	0
2	1	0	1	0	1	0	0	0	0
3	1	0	1	1	0	0	0	0	1
4	1	0	0	1	1	0	0	0	0
5	1	0	0	0	3	0	0	0	0
6	1	1	0	0	1	0	0	0	0
7	1	1	1	0	1	1	0	0	0
8	2	0	0	0	0	0	0	0	1
9	2	0	0	0	0	0	0	0	0
10	2	1	0	0	0	0	0	0	1
11	2	0	0	0	1	0	0	0	0
12	2	0	1	0	0	0	1	0	0
13	2	0	0	0	0	0	0	0	0
14	2	1	1	0	0	0	0	2	0
15	2	1	0	0	0	0	1	1	1

Appendix IV.11 Statistical results for experiment 5: Analysis 4. Response times.

i. Ammended data for response times.

	Group	Joystick a	Joystick b	Joystick c	Joystick d	Toggle a	Toggle b	Toggle c	Toggle d
1	1	11.34	15.59	15.85	15.83	13.92	14.14	13.65	15.42
2	1	20.81	13.83	17.60	20.81	9.30	9.32	9.93	9.04
3	1	16.85	15.08	19.34	22.10	16.03	18.46	23.77	23.77
4	1	10.60	11.10	13.10	12.83	9.33	10.24	10.24	10.00
5	1	13.34	11.84	12.59	11.84	7.80	6.02	9.10	7.21
6	1	14.85	16.57	15.33	18.60	11.13	13.97	16.44	13.34
7	1	4.60	5.62	6.14	5.38	7.04	7.07	7.70	8.36
8	2	13.59	23.09	19.07	18.58	16.16	19.82	18.03	21.29
9	2	18.35	23.58	25.83	18.58	14.46	19.36	24.20	16.69
10	2	17.83	35.83	27.09	23.08	15.25	15.03	22.60	24.17
11	2	17.85	21.09	20.08	19.33	21.14	24.51	21.40	25.40
12	2	25.34	15.58	24.34	29.17	27.60	49.58	34.95	34.03
13	2	28.58	32.35	31.33	27.84	18.23	24.48	18.39	23.84
14	2	14.58	13.59	16.85	20.32	15.26	12.50	18.62	16.72
15	2	36.59	37.58	36.35	40.85	39.71	49.79	44.58	49.38

ii. ANOVA summary table.

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
G	1	4070.403	4070.403	11.504	.0048	
Error	13	4599.844	353.834			
P	1	13.339	13.339	.187	.6724	
GP	1	57.668	57.668	.809	.3848	
Error	13	926.776	71.290			1.00
C	3	183.723	61.241	9.301	.0001	
GC	3	82.206	27.402	4.162	.0119	
Error	39	256.789	6.584			.97
PC	3	10.036	3.345	.236	.8708	
GPC	3	10.639	3.546	.250	.8608	
Error	39	553.156	14.183			.42

iii. Tukey test for comparison of mean response times at each robot arm-configuration.

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. A	X	s	s	s
B. B	s	X	-	-
C. C	s	-	X	-
D. D	s	-	-	X

iv. Simple main effects of group-configuration interaction.

Effect	MSn	DFn	DFe	MSe	F	p
G at A	653.902	1	13	80.262	8.147	.01
G at B	1473.789	1	13	102.515	14.376	.00
G at C	1005.535	1	13	76.719	13.107	.00
G at D	1019.384	1	13	114.091	8.935	.01
C at O-B	7.404	3	39	6.584	1.124	.35
C at R-B	39.026	3	39	6.584	5.927	.00

v. Tukey test for comparison of mean response times at each robot arm-configuration for the robot-based subject group.

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C	D
A. A	X	s	s	s
B. C	s	X	-	-
C. D	s	-	X	-
D. B	s	-	-	X

Appendix IV.12 Statistical results for experiment 6: Analysis 1. Total errors.

i. Raw data for total error scores.

	Group	Joy front	Joy back	Joy side	Togg front	Togg back	Togg side
1	1	0	0	0	1	5	0
2	1	1	2	8	2	10	8
3	1	0	5	1	4	4	2
4	1	1	0	2	0	1	2
5	1	0	0	3	0	1	2
6	2	2	6	17	5	11	4
7	2	0	3	1	0	4	6
8	2	2	5	9	0	3	1
9	2	0	2	1	1	1	1
10	2	1	2	10	4	8	11
11	2	1	5	4	1	5	4
12	2	1	3	3	1	1	0

ii. ANOVA summary table (transformed data).

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
G	1	2.571	2.571	1.744	.2161	
Error	10	14.741	1.474			
P	1	.576	.576	1.396	.2647	
GP	1	1.068	1.068	2.587	.1388	
Error	10	4.128	.413			1.00
O	2	7.463	3.732	12.628	.0003	
GO	2	.270	.135	.457	.6398	
Error	20	5.910	.296			.81
PO	2	1.342	.671	3.074	.0685	
GPO	2	.248	.124	.569	.5749	
Error	20	4.366	.218			1.00

iii. Tukey test for comparison of mean errors at each orientation (transformed data).

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C
A. Front	X	s	s
B. Back	s	X	-
C. Side	s	-	X

Appendix IV.13 Statistical results for experiment 6: Analysis 2. Direction errors.

i. Raw data for direction errors.

	Group	Joy front	Joy back	Joy side	Togg front	Togg back	Togg side
1	1	0	0	0	0	4	0
2	1	0	2	6	2	9	7
3	1	0	2	1	3	4	2
4	1	1	0	1	0	1	2
5	1	0	0	3	0	1	2
6	2	2	6	12	2	10	2
7	2	0	2	0	0	4	5
8	2	0	3	9	0	3	1
9	2	0	2	1	1	1	0
10	2	1	2	8	3	7	9
11	2	1	5	2	1	5	2
12	2	0	2	3	1	1	0

ii. ANOVA summary table (transformed data).

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
G	1	1.707	1.707	1.329	.2758	
Error	10	12.846	1.285			
P	1	.987	.987	3.412	.0945	
GP	1	1.006	1.006	3.475	.0919	
Error	10	2.894	.289			1.00
O	2	8.488	4.244	15.501	.0001	
GO	2	.419	.209	.765	.4785	
Error	20	5.476	.274			.86
PO	2	1.579	.789	3.293	.0581	
GPO	2	.407	.204	.849	.4427	
Error	20	4.795	.240			.86

iii. Tukey test for comparison of mean errors at each orientation (transformed data).

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C
A. Front	X	s	s
B. Side	s	X	-
C. Back	s	-	X

Appendix IV.14 Statistical results for experiment 6: Analysis 3. Control errors.

i. Raw data for control errors.

	Group	Joy Front	Joy Back	Joy Side	Togg Front	Togg Back	Togg Side
1	1	0	0	0	1	1	0
2	1	1	0	2	0	1	1
3	1	0	3	0	1	0	0
4	1	0	0	1	0	0	0
5	1	0	0	0	0	0	0
6	2	0	0	5	3	1	2
7	2	0	1	1	0	0	1
8	2	2	2	0	0	0	0
9	2	0	0	0	0	0	1
10	2	0	0	2	1	1	2
11	2	0	0	2	0	0	2
12	2	1	1	0	0	0	0

Appendix IV.15 Statistical results for experiment 6: Analysis 4. Task completion time.

i. Raw data for task completion times.

	Group	Joystick F	Joystick B	Joystick S	Toggle F	Toggle B	Toggle S
1	1	134.3	143.3	164.3	130.0	152.0	126.0
2	1	140.3	149.3	180.3	145.0	157.0	157.0
3	1	136.3	143.3	142.3	126.0	131.0	130.0
4	1	152.3	137.3	146.3	147.0	142.0	164.0
5	1	114.3	130.3	136.3	121.0	128.0	123.0
6	2	152.3	159.3	124.3	128.0	145.0	137.0
7	2	139.3	142.3	154.3	125.0	133.0	136.0
8	2	141.3	155.3	151.3	119.0	121.0	127.0
9	2	144.3	152.3	151.3	144.0	137.0	152.0
10	2	136.3	148.3	114.3	136.0	149.0	156.0
11	2	135.3	170.3	165.3	130.0	156.0	147.0
12	2	132.3	168.3	148.3	133.0	135.0	125.0

ii. ANOVA summary table.

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsilon Correction
g	1	12.857	12.857	.032	.8625	
Error	10	4074.143	407.414			
p	1	986.877	986.877	5.513	.0408	
gp	1	131.657	131.657	.736	.4112	
Error	10	1790.010	179.001			1.00
o	2	1420.082	710.041	7.033	.0049	
go	2	387.693	193.846	1.920	.1727	
Error	20	2019.057	100.953			.99
po	2	36.396	18.198	.189	.8292	
gpo	2	591.007	295.504	3.070	.0687	
Error	20	1925.076	96.254			.71

iii. Tukey test for comparison of mean task completion times at each human-robot orientation.

Upper Triangle: .05 level ; Lower Triangle: .01 level

	A	B	C
A. Front	X	s	s
B. Side	-	X	-
C. Back	-	-	X

APPENDIX V

PUMA ROBOT MOVEMENTS UNDER DIFFERENT ROBOT STATUS CONDITIONS

This appendix shows the appearance of individual joint movements for the three major degrees of freedom (joints 1, 2 and 3) when viewed under different conditions of robot status. These are presented in chart form showing the four conditions of human-robot orientation (front, right, left and back) and the four robot arm-configuration positions (A, B, C and D) examined in the present research work.

All of the robot movements illustrated are movements in the positive direction in accordance with the PUMA robot system. It can be seen that motion reversals for joint 1 are produced by changes in human-robot orientation. For joints 2 and 3, in accordance with the linear movement terminology (up/down), motion reversals are produced by changes in robot arm-configuration from RIGHTY (positions A and B) to LEFTY (positions C and D).

Appendix V. Chart illustrating movements of joints 1, 2 and 3 in the positive direction and the motion reversals produced by changes in robot status