University of Southern Queensland

Faculty of Engineering and Surveying

THE DEVELOPMENT OF A WRIST REHABILITATION DEVICE FOR MOVEMENT THERAPY

A dissertation submitted by

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in fulfilment of the requirements of

Courses ENG4111 and 4112 Research Project

towards the degree of

Bachelor of Engineering (Mechatronics)

Submitted: October, 2009

ABSTRACT

The loss of motor control and strength as a result of stroke can be effectively treated through physical rehabilitation including movement therapy. This project aims to automate the administration of such therapy by designing and developing a computer based device for the rehabilitation of the wrist. The device is to target the two degrees of freedom of the wrist as well as forearm rotation.

A prototype rehabilitation device has been constructed and software has been developed to represent movement of the wrist in an onscreen virtual environment. A simple and entertaining video game encourages the patient to move their wrist through an appropriate range of motion, emulating movement therapy. Testing of the system found that the device is successful in capturing a large range of wrist movement and the representation of position in the virtual environment is accurate.

The rehabilitation device developed in this study demonstrates the potential for automation of movement therapy using computer based systems. Further development of the device has been recommended, including the implementation of force-feedback so that the system can actively assist and resist patient movement. Work undertaken in this project represents a significant step towards the automation of physical therapy for rehabilitation of stroke.

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ACKNOWLEDGMENTS

I would like to thank Dr Selvan Pather for his dedicated supervision and invaluable guidance provided during the undertaking of this project.

To my family and friends, I wish to extend my sincere gratitude for your continual support and encouragement.

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GLOSSARY

Throughout this dissertation, the following abbreviations will be used:

ADC:	Analogue to Digital Conversion
ADL:	Activity of Daily Living
AutoCITE:	Automated Constraint Induced Therapy Extension
CIMT:	Constraint Induced Movement Therapy
CPW:	Continuous Passive Movement
IDE:	Integrated Development Environment
LCD:	Liquid Crystal Display
ROM:	Range Of Motion
SCARA:	Selective Compliance Assembly Robot Arm
USB:	Universal Serial Bus

Chapter 1 INTRODUCTION

1.1 INTRODUCTION

The last century has seen an amazing advance in technology, including the emergence of computers, robotics and automation. Industry has embraced these technologies, particularly in the manufacturing sector where robots have replaced humans to perform repetitive or dangerous tasks. As robotics and computers gain widespread acceptance and become increasingly affordable, new and ingenious uses continue to present themselves. Recently, the field of medicine has realised the potential applications of computer based systems in helping doctors diagnose, operate on and rehabilitate patients with greater precision, efficiency and repeatability than traditional methods.

The focus of this dissertation is the design and development of a therapy device to assist physiotherapists in the rehabilitation of a patient's wrist strength and motor control which have been impaired by stroke. This chapter outlines the purpose, objectives and methodology of this project as well as providing an overview to the dissertation.

1.2 MOTIVATION

Stroke is a growing concern in Australia, with 60 000 people expected to suffer from a stroke in 2009 (NSFA 2009). Unfortunately, this number is expected to steadily increase due to the ageing population in Australia. According to data collected by the Australian Institute of Health and Welfare, half of all stroke victims will be left with a disability (Senes 2006, p. 3). The effects of stroke include physical and neurological impairment which often lead to serious loss of independence physically, socially and financially. Hence, we can clearly identify a growing problem – the rehabilitation of these stroke victims who have suffered a disability.

More specifically, this project is concerned with those stroke victims who have lost their pre-stroke motor control and dexterity in their wrists. Many researchers have found that the plasticity of the brain permits motor control recovery by repetitive physical therapy. Plasticity refers to the reorganisation of the brain in response to change such as the brain trauma induced by stroke (Donoghue & Rioult-Pedotti 2003, pp. 1-15).

Current physical therapy of stroke patients is generally administered one-on-one with the patient by physiotherapists. This involves the physiotherapist guiding and motivating the patient through several repetitive exercises which target the affected area and stimulate brain plasticity. However, traditional physiotherapy is labour intensive, time consuming and vulnerable to human error in patient assessment.

This project aims to provide a better solution – automated computer based therapy to assist the therapist in administrating these repetitive tasks with greater repeatability, accuracy and entertainment whilst reducing the physical exertion and time commitment. A computer based automated therapy is also ideal for quantitatively monitoring and adapting to patient progress.

1.3 PROJECT OBJECTIVES

This project endeavours to design, construct and test a low-cost computer based therapy system to assist in the rehabilitation of stroke patients. A systematic list of objectives has been constructed in order to achieve this overall goal. These objectives are:

1. Investigate stroke and its effects on the human body.
2. Research current wrist rehabilitation techniques.
3. Critically evaluate existing wrist rehabilitation devices.
4. Design, detail and construct a therapy device.
5. Develop software which allows the patient to control a computer game with the device.
6. Test the device and evaluate its effectiveness as a therapy aid.

If time permits:

7. Integrate force-feedback into the design and analyse its value.
8. Suggest improvements and outline future work.

1.4 METHODOLOGY

Background research will be undertaken in order to gain a broad understanding of all the relevant factors involved in the development of a wrist therapy device. These topics include the effects and current treatments of stroke, wrist physiology, existing therapy devices and their effectiveness as therapeutic aids. This literature review will assist in the conceptualisation of several possible designs of a therapy device.

The device will target two degrees of wrist rotation as well as rotation of the forearm and should aim to accommodate as much range of movement as possible. To be an effective therapy aid, the device should have high back-driveability, low friction and minimum set up time. The system should also be simple and cheap enough to allow patients to exercise in their own home rather than be restricted to a hospital.

Simple computer games will be developed using the device as their input. These virtual worlds will interact with the patient to increase motivation whilst giving the physiotherapist a high degree of control over the exercise regimes. The software will aim to encourage cognitive activity via visual feedback, log movement and quantitatively monitor patient progress.

Critical analysis of these designs will be undertaken and result in one design being further developed. A prototype will be created in 3D modelling software to help visualise the design and validate its functionality. From this model, detailed workshop drawings will be produced in consultation with USQ workshop staff who will construct the prototype.

Testing of the prototype will ensue to make sure that the device meets the design requirements and to identify any necessary improvements. Basic mechanical testing should verify that the device can adequately record natural wrist movements whilst not being overly intrusive or uncomfortable to the user. Furthermore, it is hoped that the device can be demonstrated to a physiotherapist so that their professional opinion can be appreciated.

Electrical hardware and computer software will then be developed in order to translate movement of the device to a virtual environment in the form of a simple computer game. This software must be tested to ensure that physical movement of the device is precisely captured in the virtual representation on the computer screen. If time permits, a force feedback system will be implemented to change the passive device to an active rehabilitation aid. Further testing of this force feedback system is also expected.

1.5 Outline of Chapters

The remainder of this dissertation will be structured as follows:

Chapter 2: Background

This chapter reviews and summarises literature relating to the design of a rehabilitation robot including wrist biomechanics, stroke and current therapy techniques.

Chapter 3: Concept Design

Several possible concept designs are presented here along with a critical analysis of their suitability as therapy devices.

Chapter 4: Prototype Design

This chapter will outline the progression of a concept into a working prototype, including detail drawings, stress analysis and component selection.

Chapter 5: Software Development

This chapter will document the design and development of software for the computer and data acquisition hardware.

Chapter 5: Testing & Analysis

A discussion of how well the system meets established requirements will be presented here along with relevant testing procedures and results.

Chapter 6: Conclusion

Finally, this chapter will summarise the effectiveness of the therapy device and recommend future development of the design.

1.6 Conclusion

The aim of this project is to design, construct and test a device to assist in wrist rehabilitation of stroke patients. This will involve background research of relevant literature, design of a suitable prototype, development of software to interact with the device, testing and critical evaluation of the system as an effective therapy aid.

The prevalence of stroke in Australia and limitations of current stroke therapy techniques justify the need for the development of a computer based therapy system. This device is intended to relieve the physical therapist from the physical and time burdens imposed by tradition movement therapy. The patient will benefit from being able to rehabilitate at home through participation in visually stimulating video game.

Chapter 2 BACKGROUND

2.1 INTRODUCTION

A thorough literature review was conducted to gain a broad understanding of the factors involved in developing a stroke therapy device. The literature review in this chapter will investigate the anatomy, movement and motor control of the human wrist. It will also explore stroke, its effects on the body and existing stroke therapies. Finally, a brief overview of existing therapy robots will be presented. This information will direct the design of the therapy device as well as validate the objectives of this project.

2.2 WRIST BIOMECHANICS

The human wrist performs the seemingly straightforward role of connecting the hand to the forearm. However, its biomechanics are far more complex and intricate than the simple superficial movements of the wrist would suggest. This section will briefly detail the anatomy and articulation of the wrist along with the presentation of supporting anthropometric data.

2.2.1 WRIST ANATOMY

The wrist connects the five metacarpal bones of the hand to the ulna and radius bones of the forearm through a series of small bones, muscles and component joints which give it extraordinary flexibility and range of motion (Encyclopaedia Britannica 2009). Figure 2-1 illustrates the eight small carpal bones of the wrist which link the metacarpals to the forearm. The eight carpal bones are approximately arranged into two rows, called proximal and distal rows.

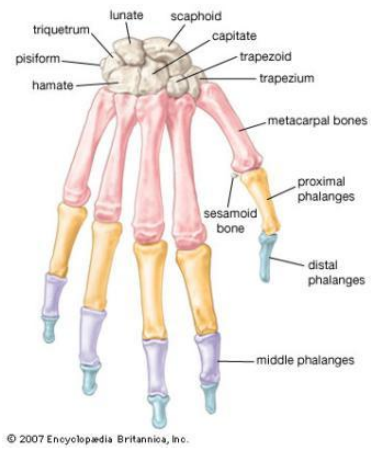

FIGURE 2-1: BONES OF THE HAND, INCLUDING THE CARPAL BONES (ENCYCLOPAEDIA BRITANNICA 2007).

These carpal bones are governed by more than 20 carpal joints, 26 named ligaments and 6 parts of the triangular fibrocartilage complex (Dutton 2004, p. 582). The major ligaments in the wrist are identified and illustrated in Figure 2-2.

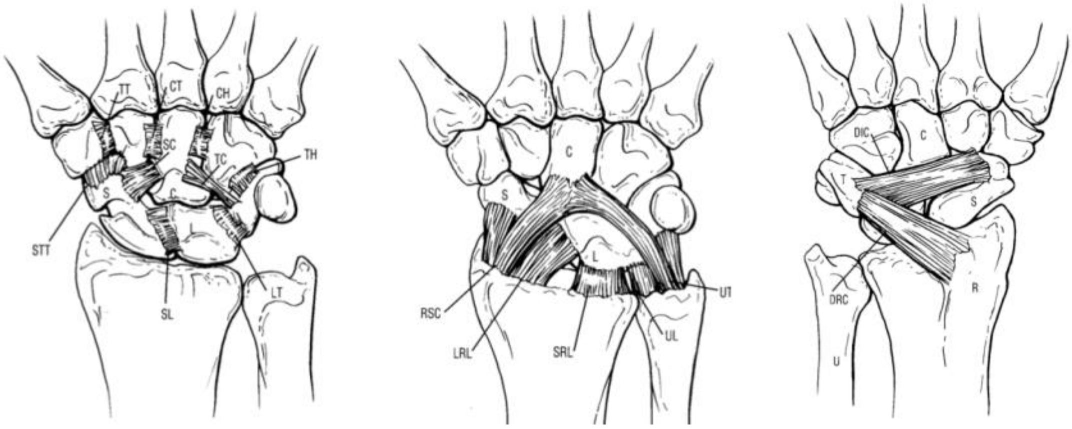

FIGURE 2-2: LOCATIONS OF THE MAJOR LIGAMENTS IN THE WRIST (HERNDON 1999).

All of these interrelated components work together to permit an amazing degree of dexterity in the wrist. Further detailed examination of wrist anatomy is not necessary to fulfil the objectives of this project. However, the articulation mechanisms of the wrist joint are important and will be explored in depth.

2.2.2 WRIST ARTICULATION

The wrist joint is capable of two degrees of rotation, which allow it to form the postures depicted in Figure 2-3.

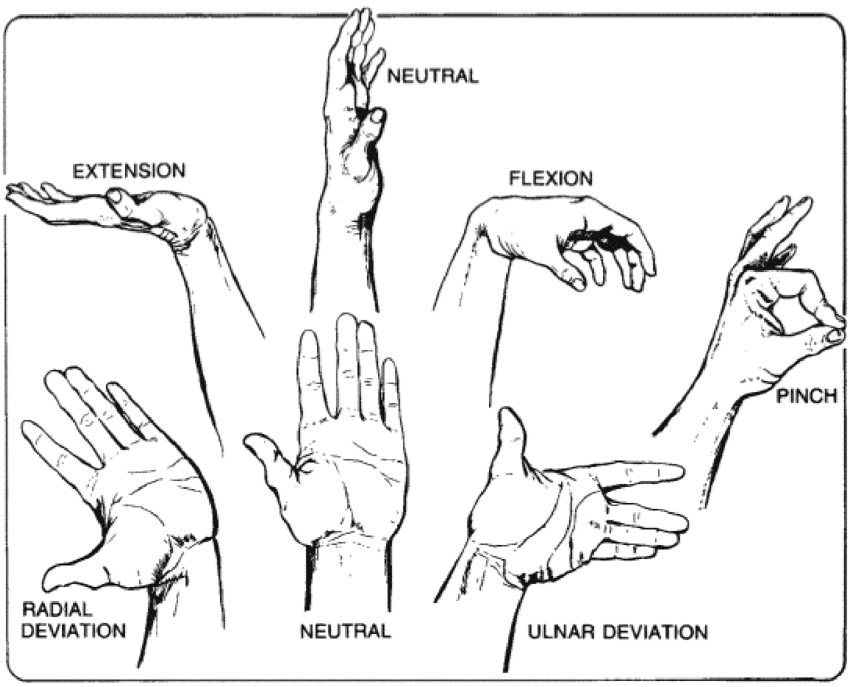

FIGURE 2-3: DEPICTION OF HAND AND WRIST POSTURES (PUTZ-ANDERSON 1988, P. 54).

The two degrees of freedom in the wrist are shown in Figure 2-4 and allow four different movements as indicated by the arrows. Extension (arrow 2) and flexion (arrow 1) are rotations about axis AA' and radial deviation (arrow 4) and ulnar deviation (arrow 3) are rotations about axis BB'. It should be noted that the terms abduction and adduction can be used interchangeably with radial deviation and ulnar deviation respectively.

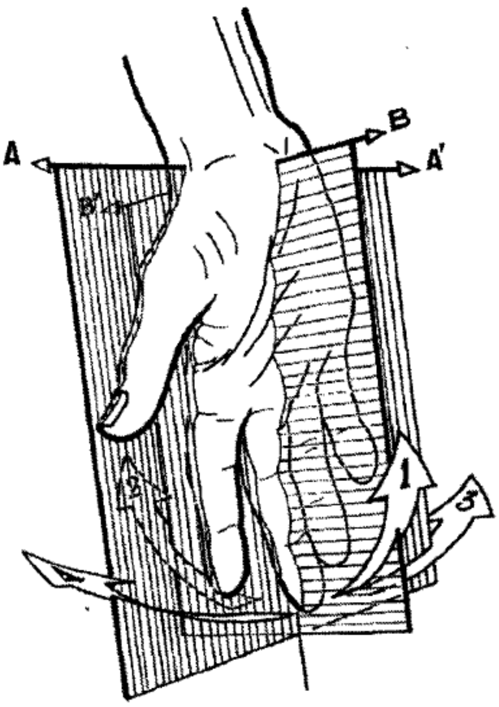

FIGURE 2-4: WRIST MOVEMENT AXES OF ROTATION. (KAPANDJI 1970)

Anthropometric data collected by Barter *et. al.* (1957) and compiled by Pheasant (2003) gives the range of motion in the wrist for the 5th, 50th and 95th percentile male as shown in Table 2.1.

TABLE 2-1: JOINT RANGE DATA. (PHEASANT 2003)

Joint	5th %ile	50th %ile	95th %ile	SD
1. Shoulder flexion	168	188	208	12
2. Shoulder extension	38	61	84	14
3. Shoulder abduction[a]	106	134	162	17
4. Shoulder adduction	33	48	63	9
5. Shoulder medial rotation	61	97	133	22
6. Shoulder lateral rotation	13	34	55	13
7. Elbow flexion	126	142	159	10
8. Pronation[b]	37	77	117	24
9. Supination[c]	77	113	149	22
10. Wrist flexion	70	90	110	12
11. Wrist extension	78	99	120	13
12. Wrist abduction (radial deviation)	12	27	42	9
13. Wrist adduction (ulnar deviation)	35	47	59	7

Further research by Kapandji (1970) realises error induced by finger adduction and gives a better indication of actual wrist motion. This data concludes that the human wrist is capable of moving 85° from the neutral position in both flexion and extension, as shown in Figure 2-5Figure 2-1. Radial deviation has a range of 15° and ulnar deviation a range of 30°, as illustrated in Figure 2-6.

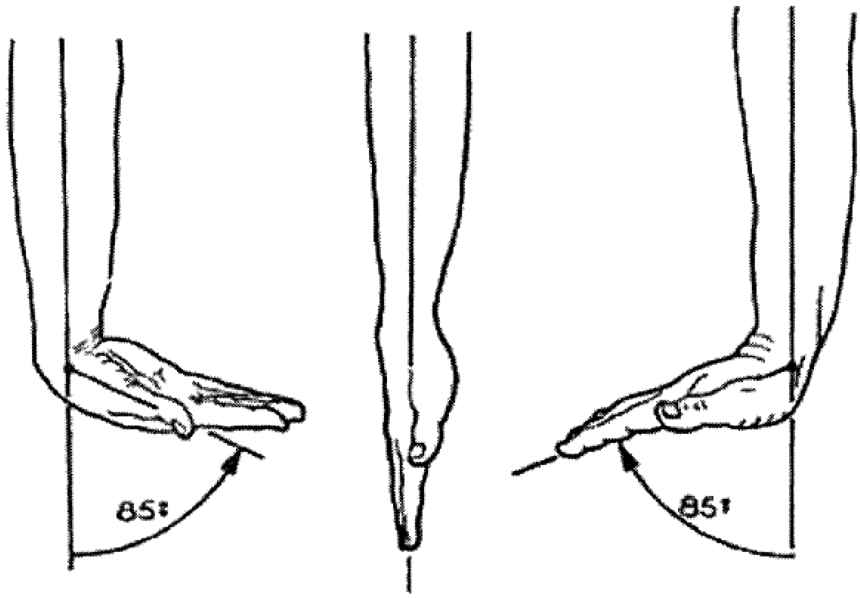

FIGURE 2-5: FLEXION (LEFT) AND EXTENSION (RIGHT) OF THE WRIST (KAPANDJI 1970).

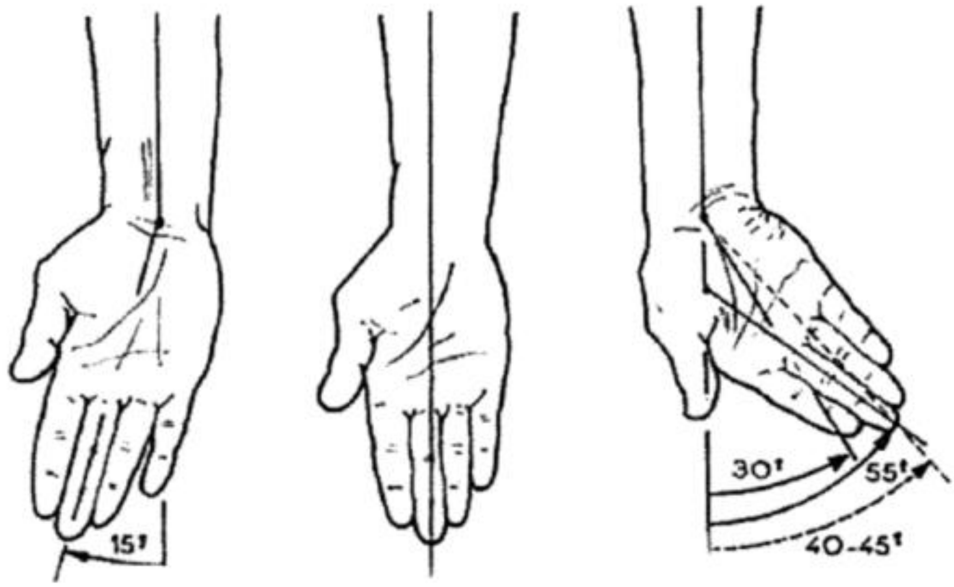

FIGURE 2-6: RADIAL DEVIATION (LEFT) AND ULNAR DEVIATION (RIGHT) OF THE WRIST (KAPANDJI 1970).

All subtleties aside, the bi-axial nature of the wrist joint is indicative of a Cardan joint, perhaps better known as a universal joint. This joint, illustrated in Figure 2-7, attaches the hand (Body 1) to the forearm (Body 2), allowing motion about two perpendicular intersecting axes. These axes represent those about which wrist adduction/abduction and flexion/extension occur.

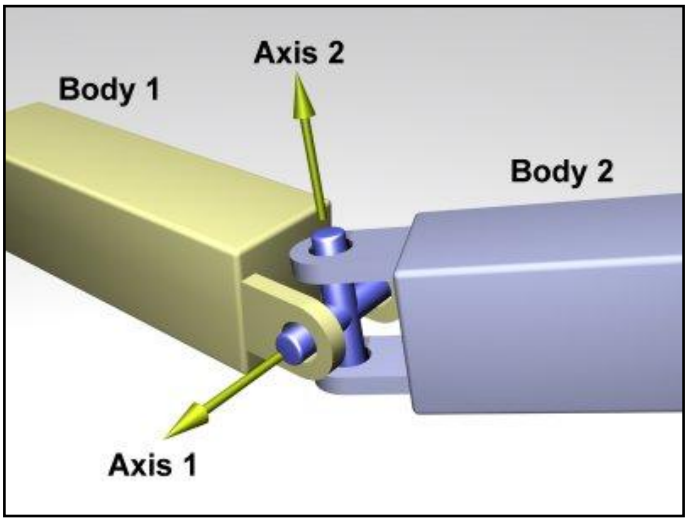

FIGURE 2-7: MECHANICAL NATURE OF A CARDAN JOINT.

However, due to the intricacies of the anatomical structure of the wrist, the four gross motions discussed above are not entirely independent of one another. For example, when the wrist is fully extended or flexed, radial and ulnar deviation is significantly decreased due to tension developed in the carpal ligaments (Kapandji 1970). The coupling of the flexion, extension, adduction and abduction motions is best illustrated in Figure 2-8 which depicts the extent of available wrist movement as the so called 'cone of circumduction'.

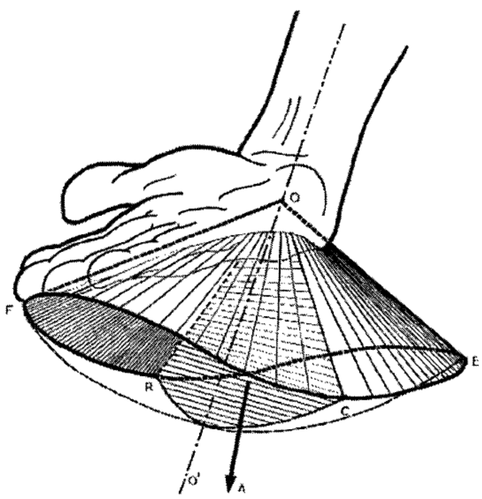

FIGURE 2-8: THE "CONE OF CIRCUMDUCTION" DEPICTING AVAILABLE WRIST MOVEMENT (KAPANDJI 1970).

2.2.3 *Forearm Articulation*

Although forearm articulation is not strictly a motion of the wrist joint, it is closely related and will be targeted by the therapy device. Rotation of the forearm occurs about its longitudinal axis and results from the movement of the long ulnar and radial bones around one another. This articulation is called pronation and supination, as depicted in Figure 2-9, and is measured with the elbow bent so to eliminate shoulder rotation.

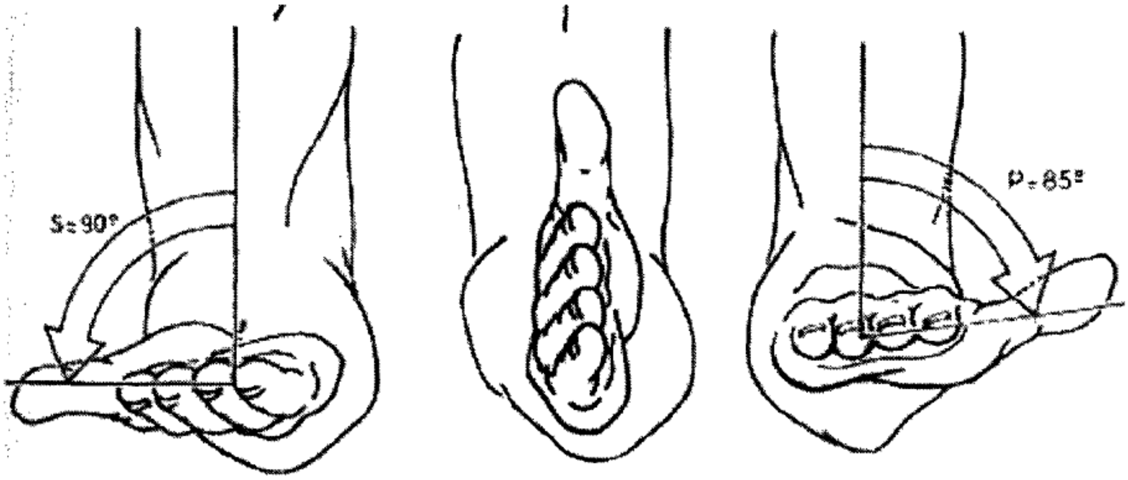

Figure 2-9: Supination (left) and pronation (right) of the forearm (Kapandji 1970).

The total rotation range of forearm rotation is nearly 180° with 90° of supination and 85° of pronation about the neutral position (Kapandji 1970). Articulation of the forearm is also coupled to wrist motion by ligament structure. This is observed as a reduction of flexion and extension in the wrist when the forearm is pronated. Similarly, supination allows greater abduction than pronation. Hence, forearm articulation is closely tied to wrist movement.

2.3 STROKE

This section aims to briefly outline the mechanisms of stroke and how it affects its victims physically, neurologically and emotionally.

2.3.1 DEFINITION

By definition, stroke refers to brain damage caused by an abnormality in the blood flow to a certain part of the brain (Caplan 2006, p. 6). Blood carries oxygen and sugar to the brain so that it can function properly. When this blood supply is interrupted by a stroke, brain injury occurs very rapidly. Stroke can be divided into two broad types – ischemia and haemorrhage which account for 85% and 15% of instances respectively (Senes 2006, p. 2).

Ischemia occurs when the blood supply to the brain is inadequate. Interruption to the blood supply is a consequence of thrombosis, embolism or systemic hypoperfusion (Caplan 2006, pp. 10-18). Thrombosis is where the arteries narrow, severely restricting blood flow and encouraging clotting. An embolism occurs when fatty material at a donor site breaks off and travels through the arteries to the brain where it forms a clot in a blood vessel. Inadequate performance of the heart, causing low blood pressure, also leads to diminished blood flow to the brain and is called systemic hypoperfusion. Prolonged ischemia results in brain damage, called an infarction, from the lack of oxygen and glucose.

Haemorrhage occurs when blood vessels within the brain rupture, causing internal bleeding. Soft brain tissue is torn as a result of this bleeding, disconnecting vital nerve centres and pathways. Haemorrhage is categorised by its location in the brain but is almost always a result of hypertension (high blood pressure). Figure 2-10 depicts the effects of haemorrhagic and ischemic stroke on the brain.

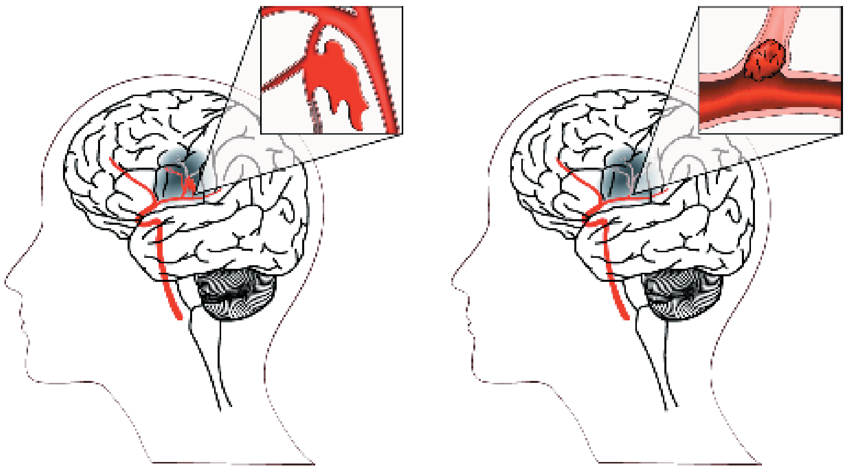

FIGURE 2-10: HAEMORRHAGIC STROKE (LEFT) AND ISCHEMIC STROKE (RIGHT) (NSFA 2009).

2.3.2 Outcomes

Stroke is a major concern in Australia, killing 9006 people in 2003 and leaving 146 400 with a disability (Senes 2006). As the population ages, these numbers are destined to increase by 2-3% per year since the elderly are most at risk. As demonstrated in Figure 2-11, a person's risk of suffering a stroke increases dramatically after the age of 65.

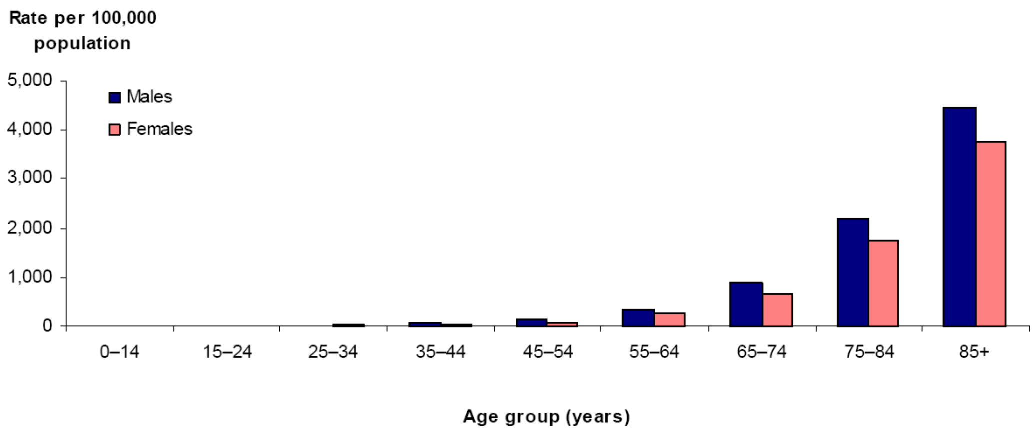

Figure 2-11: Stroke attack incidents in Melbourne, 1996-97 (Thrift 2000).

Most stroke victims are disabled immediately after a stroke attack and one in five will die within the first month (Thrift 2000). The specific nature and location of impairment depends on where the stroke occurred in the brain, the right hemisphere, left hemisphere, cerebellum or brain stem (Corbett 2009). Common symptoms of a stroke attack are permanent paralysis or weakness of one side of the body, called hemiplegia or hemiparesis respectively. Difficulty speaking or swallowing, memory loss, personality change and cognitive impairment are also experienced by some stroke victims. This project is primarily concerned about the loss of motor control caused by damage to the central nervous system.

Motor control impairment manifests itself almost immediately after a stroke attack as a loss of movement on the affected side of the body (hemiparesis) and involuntary muscle activations (Celestino 2003). Stroke victims will also experience increased resistance to passive movement due to the onset of spasticity and contracture, which affect the muscle and tendon structure. Synkinesis is frequently witnessed in stroke patients and is characterised by unintentional movement patterns associated with an intended motor action (Twitchell 1951).

It is not only loss of motor control which make life difficult for stroke victims, but also the cognitive and perceptual impairments. Hemiparesis often involves a severe decrease in sensation and perception on the affected side of the body. This hinders the motor control feedback loop, the complex system of communication between the muscles and the central nervous system. The brain may then choose to neglect the affected limb, resulting in non-use and muscle degradation.

These disabilities severely reduce the independence of stroke victims, half of which still remain dependent on others to perform daily tasks one year after the attack (Hankey et al. 2002). It is not surprising then to learn that many stroke survivors rate their quality of life as being very poor, two years after the attack (Sturm et al. 2004). The important fact is that the independence and quality of life of stroke patients can be greatly improved by rehabilitation.

2.4 REHABILITATION

The broad aim of post-stroke rehabilitation is to restore the independence of stroke survivors physically, psychologically, socially and financially to the highest possible degree (Senes 2006). Early intervention is the key to successful recovery from stroke (NSFA 2009) and involves a team of health professionals including physical, occupational and speech therapists. Stroke rehabilitation is a highly individualised process as each patient will exhibit different levels and types of impairment.

To grasp an understanding of why rehabilitation can help a stroke victim, an appreciation of brain plasticity is essential.

2.4.1 BRAIN PLASTICITY

A remarkable quality of the human brain is ability to self-reorganise after a traumatic or abnormal experience (Donoghue & Rioult-Pedotti 2003). Self-reorganisation occurs thanks to the inherent plasticity of the brain, which is characterised by the dynamic modification of neural pathways. This mechanism may occur in response to learning, sensory experience, pathological change or as a consequence of brain trauma. Essentially, this means that the brain can reassign or relearn important functions that have been impaired as a result of brain damage elsewhere.

Hence, brain plasticity is at the core of stroke rehabilitation, as it promises the possibility of motor control recovery. It is well documented that limb stimulation leads to synaptogenesis, that is the reestablishment of neural pathways that control volitional movement (Krebs et al. 2007). By utilising neuro-imaging and transcranial magnetic stimulation, Taub *et al.* (1999) concluded that movement therapy encourages synaptogenesis. Casadio *et al.* (2009) concur with this hypothesis, stating that by simply using the affected limb, neural plasticity facilitates functional recovery of motor control. It is this phenomenon which makes physical therapy so essential to the rehabilitation process.

2.4.2 Physical Therapy

The goal of stroke therapy is to restore as much independence to the stroke patient as possible within the bounds of their permanent neurological damage. This project is more specifically aimed at restoring strength, motor control and cognitive ability, which are key elements to regaining functional use of the wrist.

Before looking at current treatments, the distinction should be made between the physical and occupational therapist, both of which have key roles in the rehabilitation process. The physical therapist is concerned with diagnosing and restoring the actual physiological damage caused by the stroke. On the other hand, the occupational therapist teaches the patient new ways to compensate for their disability so that they can perform activities of daily living (ADL), such as opening a jar. Because this project is primarily aimed at the restoration of physical and cognitive ability, the rest of this discussion will be limited to physical therapy only.

Early adoption of a rehabilitation strategy is extremely important as it has been proven that the most significant recovery can occur within the first three months following the stroke. Disturbingly, a survey of Australian stroke patients has found that little rehabilitation occurs within the first fortnight (Bernhardt et al. 2004).

Physical therapists currently work with patients one-on-one, assisting and guiding them through a series of repetitive exercises, tailored to their specific impairments and time since stroke. Initially, these activities will include the physical therapist repetitively stretching the patient's wrist and forearm through its range of movement (ROM) in what are known as continuous passive motion (CPM) exercises. Although ROM & CPM exercises are successful at combating stiffness and muscle contracture, there is little patient involvement or neural stimulation in the process.

As the patient regains some control of the limb, they often undertake other activities which require more participation on their behalf, including strengthening and resistance exercises. These require the patient to not only resist static forces but also to move against them. Force may be physically generated by the therapist or by stacking various numbers of weights on a specialised wrist exercising machine.

A program of rehabilitation activities which has shown great promise is constraint induced movement therapy (CIMT). This was developed by Taub *et al.* (1999) and derives its name from the fact that the patient is forced to use the affected limb by applying restraints to unaffected limbs. This discourages the brain from avoiding using the affected area in favour of healthy limbs, a phenomenon dubbed 'learned non-use' by Taub *et al.* (1999).

CIMT also requires intensive massed practice on behalf of the patient, often up to 90% of waking hours a day over a three week period (Lum et al. 2004). Typical activities include those which associated skills can transfer directly to the patient's daily life including reaching for, picking up, squeezing, placing and otherwise manipulating different objects. The peg-board activity, for example, requires the patient to pick up different size pegs and place them into their corresponding holes.

CI movement therapy is an incredibly time intensive and expensive treatment as it requires a significant amount of one-on-one interaction with a physical therapist. Recognising that many patients who would benefit from this treatment would not be able to afford it, researchers began looking for ways to automate the therapy. This sparked the recent development by Lum *et al.* (2004) of the automated equivalent of CIMT, called the AutoCITE (Automated Constraint Induced Therapy Extension).

This system consists of eight activities as pictured in Figure 2-12 which are (top row) reaching, peg-board, supination/pronation, threading, (bottom row) tracing, object flipping, finger-tapping and arc-and-rings. A computer records patient progress and provides encouraging feedback to the patient at regular intervals, effectively removing the laborious one-on-one physical therapist time traditionally required.

FIGURE 2-12: THE AUTOCITE'S TASK DEVICES (LUM ET AL. 2004).

Lum *et al.* anticipate that AutoCITE will eventually be used in the patient's own home with an internet link between the workstation and a physical therapist (2004). The computer would send the therapist clear data quantifying the extent of patient progress and areas that the patient may be struggling with. This would allow the therapist to remotely modify the exercise routine in an effective and rapid manner. Technology such as AutoCITE is a huge and exciting step towards tele-rehabilitation in the home.

2.4.3 HOME-BASED THERAPY

An emerging trend in healthcare, in Australia and America at least, is the reduction of hospital services to inpatients and outpatients, in an attempt to cut costs and lessen the load on health professionals. Senes findings indicate that the median hospitalisation time of a stroke patient in Australia is only eight days and that the majority of these patients live at home post-stroke (2006, p. 10). This trend has resulted in a strong move towards community care and home-based treatments.

Whilst not designed to replace physical therapists, home-based exercises do reduce their workload and provide an additional means of self directed rehabilitation to the patient. A physical therapist will design a series of activities that the individual can conduct at home with minimal equipment or supervision. For the rehabilitation of the upper arm and shoulder, these may include placing a cloth between the lower arm and the table to reduce friction and then moving the arm through a number of positions.

For the wrist however, the number of exercises that can be prescribed are few and often require expensive equipment. One simple exercise, as described by Kamal, is rolling and manipulating balls of various sizes with the hands and wrist to promote tactile awareness (1987). Clearly though, there is a need for cheap and accessible equipment for wrist rehabilitation in the home.

2.4.4 Patient Assessment

In order to quantify patient improvement or regress as a result of rehabilitation or lack thereof, physical therapists administer various motor function tests periodically throughout the course of treatment. Unfortunately many of these tests were not originally designed to assess stroke victims and as such the results are not always dependable.

The commonly used Manual Muscle Test (MMT) and Fugl-Meyer (FM) scales are rather subjective as they rely on the physical therapist judging specific movements against an ordinal scale. Others are more concerned with independence of function, such as the Functional Independence Measure (FIM) and Barthel Index which attempt to score a patient's ability to perform ADL's on the amount of assistance they require (Celestino 2003). Physical therapists also employ measuring equipment such as goniometers and dynamometers to determine range, strength and speed of limb movement.

2.4.5 Outcomes

The results of traditional therapies such as Constraint Induced Movement Therapy have been outstanding, although one must remember the magnitude of time, expense and involvement of professional therapists which they demand. Over the last decade, many clinical trials have been undertaken in an effort to quantify how well rehabilitation programs improve a stroke patient's quality of life.

Taub *et al.* and many others have proven that remarkable improvements are possible after an intensive program of CIMT (1999). In fact, researchers have found that any early rehabilitation that involves repetitive movement of the affected limb significantly improves the patient's long-term level of recovery. Of particular note is the successful level of patient improvement from using the AutoCITE workstation which Lum *et al.* found was almost identical to one-on-one physical therapy.

Figure 2-13 illustrates the level of improvement possible in just one of AutoCITE's activities after just 10 days of rehabilitation.

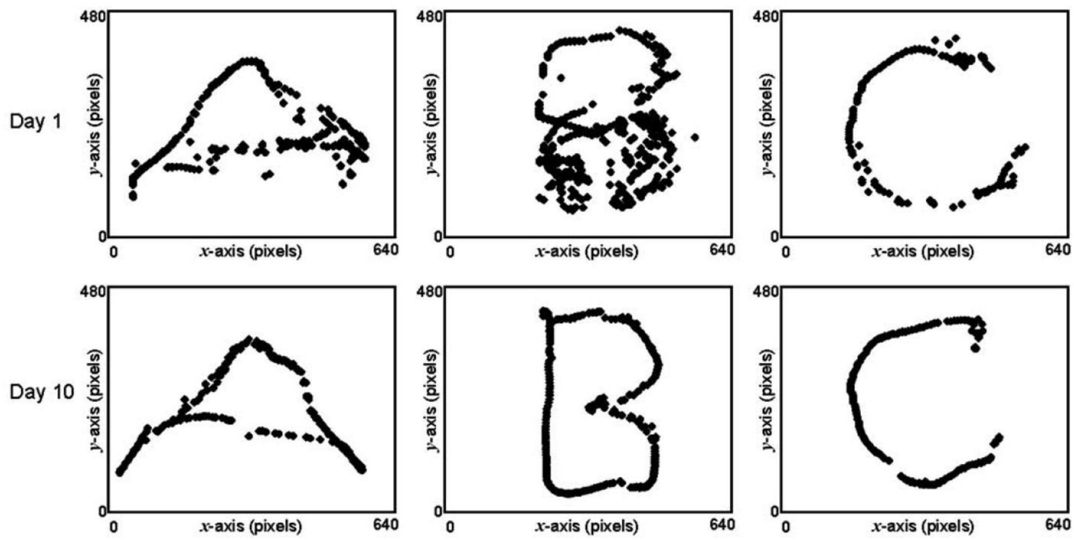

Figure 2-13: Performance of AutoCITE letter tracing task on day 1 (top) compared to day 10 (bottom) (Lum et al. 2004, p. 256).

2.5 Robot Assisted Therapy

Robotic therapy should not be thought as an alternative to traditional physical therapy but rather as a technology which has the potential to complement and enhance it. This section discusses the advantages and limitations of robot assisted therapy as well as outlines some existing therapy devices.

2.5.1 Advantages

Robot assisted therapy has the potential to enhance traditional physical therapy because of the following characteristics:

- Robots deliver a highly repeatable and consistent motor learning experience (Krebs et al. 2007).
- Robots can objectively measure patient improvement, rather than using unreliable and subjective human administered clinical scales (Colombo et al. 2005)
- Patient motivation is maintained by providing haptic and visual feedback using an interactive virtual environment.
- Active robots can change assistance levels so that the patient faces more challenging tasks as their impairment improves.
- Physical therapists can define exercise routines and monitor patient performance without the time and physical limitations of traditional therapy.

2.5.2 Limitations

Despite the numerous advantages of robot-assisted therapy, it also has its limitations:

- Simple exercise patterns that encourage smoothness of movement do not necessarily help stroke patients perform functional everyday activities such as opening a jar (Casadio et al. 2009).
- There is an absence of a defined set of guidelines by which patient improvement is measured (Celik et al. 2008).
- Very little comparison has been made between clinical and robotic measures of patient impairment.
- Most therapy robots that have been developed are restricted to hospitals and rehabilitation centres because of their complexity and high cost.
- Decreased intimacy between patients and their therapists.

2.5.3 *Therapy Robots*

Robotic therapy has not yet gained widespread acceptance due to the high success and familiarity of traditional physiotherapy. However, over time physical therapists are realising the potential of therapy robots as an aid rather than viewing them as competitors (Hesse, Schmidt & Werner 2006). A small number of electromechanical and passive exercise devices have been developed to assist in stroke rehabilitation. Interestingly, most of these devices have been designed to target the upper proximal extremities such as the shoulder and elbow. Only a handful of robots have been developed to rehabilitate the wrist. This section will identify and briefly outline some of these devices.

2.5.3.1 MIT-MANUS

The MIT-MANUS was developed in 1991 at the Newman Laboratory for Biomechanics and Human Rehabilitation at The Massachusetts Institute of Technology (MIT). The aim of the research at MIT was to study the effectiveness of robots in encouraging the neurorehabilitation of motor function (Krebs et al. 2007). MIT-MANUS is a planar, two degree of freedom device which targets the elbow and shoulder joints. The robot is an active device which is based on a five bar parallel drive selective compliance assembly robot arm (SCARA). Patients use the end effector of the robot to manipulate an on-screen virtual environment as shown in Figure 2-14.

FIGURE 2-14: THE MIT-MANUS SET UP IN A HOSPITAL DURING CLINICAL TRIALS (KREBS ET AL. 2007).

The robot was very successful in initial clinical trials with stroke patients at Burke Rehabilitation Hospital. These patients showed significant improvement in their motor control of their shoulder and elbow which were the limbs that the device was designed to exercise. This success sparked interest into developing new modules for the MIT-MANUS which would target other muscles groups, including the wrist.

Hence an innovative wrist module was designed to be attached to the tip of the MIT-MANUS (as in Figure 2-15) or to act as an independent stand-alone device (Williams, Krebs & Hogan 2001). The wrist attachment is an active, 3-DOF device allowing all movements of the wrist to be exercised. The device uses an ingenious differential mechanism coupled with two brushless motors to apply variable torque to the patient's wrist in both flexion/extension and adduction/abduction. Another motor mounted on a curved rack governs torque about the pronation/supination axis.

FIGURE 2-15: THE MIT-MANUS DISTAL WRIST ATTACHMENT (KREBS ET AL. 2007).

The MIT-MANUS and integrated wrist attachment guides the patients hand through repetitive exercise routines which would otherwise require one on one contact with a physiotherapist. By varying the torque provided by the electric motors, patient movement can be assisted or resisted depending on their state of impairment. Patient movement data can also be logged on a computer, so any improvement can be easily quantified by a physiotherapist.

2.5.3.2 JAS Wrist

Joint Active Systems (JAS) has developed several commercially available passive exercise machines including the JAS Wrist (2004), shown in Figure 2-16. This device relies on the continuous passive motion (CPM) therapy technique where the patient repeatedly moves their wrist joint through its entire range of motion. The patient can vary the amount of resistance provided by the device so that they can progressively strengthen their wrist muscles. Only one movement can be targeted at once and there is no logging of data or computer interface.

FIGURE 2-16: JAS WRIST IN EXTENSION (TOP) AND FLEXION (BOTTOM). (JOINT ACTIVE SYSTEMS 2004)

2.5.3.3 RiceWrist

The RiceWrist was developed by O'Malley *et al*. (2006) at Rice University, as an expansion of an existing therapy robot, MIME (Mirror-Image Motion Enabler). The device resembles an exoskeleton with four degrees of freedom as shown in Figure 2-17. A base plate supports three links connecting to a moving plate via revolute pin joints and rotates to accommodate forearm supination/pronation. The three links are extendable, allowing the moving plate to tilt in two directions and translate towards and away from the base plate. This tilting movement corresponds to adduction/abduction and flexion/extension of the wrist.

The patient is required to reach through the exoskeleton and grip an end effector which is attached to the moving platform. Three lightweight motors control the length of the extendable links through a novel cable and capstan arrangement for torque control. A frameless motor also controls rotation of the base plate (forearm articulation). The RiceWrist is therefore an active device as it is able to provide force-feedback to the patient.

The MIME-RiceWrist system gives physiotherapists a high degree of governance over the therapy session. A graphical user interface (GUI) lets the therapist log movement data, assign joint range limits and set up repetitive exercise routines for individual patients. The device can be configured to act passively or actively where a variable amount of force must be overcome.

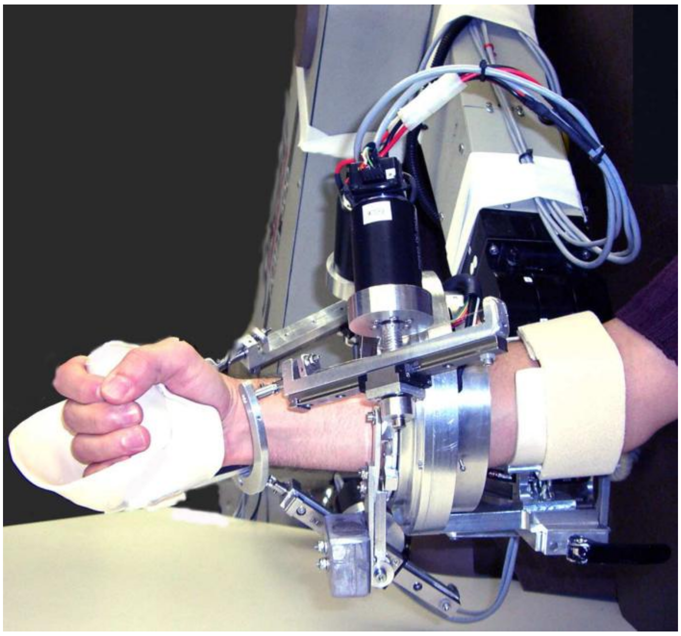

FIGURE 2-17: OPERATION OF THE RICEWRIST SYSTEM (O'MALLEY ET AL. 2006).

2.5.4 *REVIEW OF ROBOTIC THERAPY*

Although research in this area is fairly limited, robotic therapy is showing promising results in a number of clinical trials on stroke affected patients (Casadio et al. 2009). Krebs et.al. report that stroke victims with a severe to chronically severe impairment showed a 10% improvement on the Fugl-Meyer impairment scale after a 12 week initial clinical trial of the MIT-MANUS shoulder, elbow and wrist robot (2007, p. 333). This level of improvement is remarkable, proving the effectiveness of robots as stroke rehabilitation tools.

Another interesting phenomenon discovered by Krebs et. al. is that training the wrist first leads to twice as much carryover effect to the proximal shoulder and elbow limb segments than in the reverse order of training (2007). This discovery reinforces the need for more robots to be developed that target the distal limb segments such as the wrist.

Unfortunately, not many clinical trials have included a control group which receive traditional physiotherapy only. A systematic study conducted by Prange *et al.* (2006) unveiled that robot assisted therapy appears to improve motor control more than conventional therapy despite the fact that it showed no consistent improvement of functional abilities.

A topic of some controversy is whether or not active robots can provide better outcomes compared to passive devices. Kahn (2001) found that active assistance provided by the robot has no direct benefit to the patient, instead he suggests that repetitive movement of the limb alone is what stimulates recovery. Casiado *et al.* disagree with this finding, stating that repetitive movement alone in unlikely to produce long-lasting recover of function (2009).

2.6 Conclusion

Many people are affected by the physical and neurological damage brought on by stroke. These people suffer loss of independence physically, socially and financially, and most experience a very poor quality of life. Rehabilitation gives these stroke survivors an opportunity to regain some of their pre-stroke functional abilities. Robot-assisted therapy is at the cutting edge of rehabilitation technology because of the advantages it offers over traditional therapy.

Chapter 3 CONCEPT DEVELOPMENT

3.1 INTRODUCTION

The development of a number of conceptual designs is presented in this chapter. These designs will be critically analysed and their respective advantages and disadvantages identified so that a chosen design that best meets the functional requirements of a wrist rehabilitation device is found. This process provokes creative thought and is critical to the development of a thoroughly considered and well designed prototype. Further analysis of the chosen solution will be explored along with justification of design features.

3.2 DESIGN REQUIREMENTS

Before delving into the design of concept devices for wrist rehabilitation, it is imperative to identify the specific functional requirements that the device should satisfy. Many of these requirements will relate directly to the background research presented in Chapter 2 whilst others will reflect commonsense engineering design philosophy. The extent to which these functional requirements are satisfied by each of the concepts will direct the design of the prototype hardware.

3.2.1 RANGE OF MOVEMENT

The specification of this project requires the device to target all movements associated with the wrist as well as rotation of the forearm. In order to satisfy this requirement, the device should accommodate the following movements:

- Adduction/Abduction of the wrist.
- Flexion/Extension of the wrist.
- Pronation/Supination of the forearm.

The range of each targeted motion will reflect those found by Kapandji (1970) and presented in Chapter 2. It would be ideal if the device could accommodate these absolute physical limits of human wrist motion. However, the wrist is capable of a large and complex range of movement, and this expectation may be unreasonable. A more realistic expectation of the device is that it should at least meet the minimum range of movement necessary for a stroke patient to complete activities of daily living.

Many researchers have tried to determine the minimal amount of functional movement of the wrist required for independent living and self-care. Elstrom *et al.* have summarised these efforts and conclude that ADLs which involve the wrist require a combined ulnar and radial deviation of 40°, flexion of 40° and extension of 40° (2006, p. 158). Required rotation of the forearm is 70° in both supination and pronation directions. The absolute range of movement and ROMs required to complete ADLs for each targeted movement are summarised in Table 3-1 below.

TABLE 3-1: FUNCTIONAL REQUIREMENTS FOR THE DEVICE'S RANGE OF MOVEMENT.

Movement	**Desired ROM**	**Minimum ROM (ADL)**
Wrist Adduction (Ulnar Deviation)	30°	40° combined radio-ulnar deviation.
Wrist Abduction (Radial Deviation)	15°	
Wrist Flexion	85°	40°
Wrist Extension	85°	40°
Forearm Pronation	85°	70°
Forearm Supination	90°	70°

Everyday activities rarely require only one specific motion of the wrist at a time, rather a complex combination of two or more movements will be engaged. The device should therefore be capable of targeting more than one movement of the wrist and forearm simultaneously. One must also consider that the motions of the wrist are not entirely independent and are coupled to some extent. For example, when the wrist is in extension, some radial deviation occurs and ulnar deviation always accompanies flexion.

Ideally then, the device should be capable of operating within Kapandji's entire cone of circumduction' (1970) as discussed in Chapter 2. For the purpose of the following conceptual design, it is assumed that the lower arm can be fully immobilised by a restraint so that only the targeted motions of the wrist and forearm can be achieved. Design of this lower arm restraint has not been considered part of the scope of this project.

3.2.2 MOVEMENT IMPEDANCE

Stroke patients often have diminished strength and poor motor control in their wrists when they begin physical therapy. Hence, the rehabilitation device should not require the patient to exert any more force than absolutely necessary to move their affected limb. There are two sources of endpoint impedance to consider here – inertia and friction.

Inertial loading of moving parts is felt by the patient as an opposing force when attempting to accelerate the end effector of the device. This force must be reasonably low so that the movement captured is indicative of that of an unimpeded wrist. One must also consider that the acceleration of the device is likely to be very low, hence inertia felt at the end effector will be minimal. Nevertheless, the mass of moving components in the design should be minimised to keep inertia at a level which is not prohibitive to the patient.

The other source of mechanical impedance is that caused by friction. Again, a maximum allowable amount is even more difficult to quantify, particularly because of the different forms in which friction presents itself. Static friction, for instance, is considerably harder to overcome than kinetic friction, which is a significant phenomenon when considering that movement of the device will not be continuous.

The velocity dependence of friction in a plain bearing, as observed in Stribeck's curve, will also have implications on the choice of bearing adopted in the design. The three stages of lubrication and associated friction on a typical Stribeck curve are shown in Figure 3-1. Of particular importance is that all movement of the device will be rather slow, hence operation will occur within Stage III of the curve.

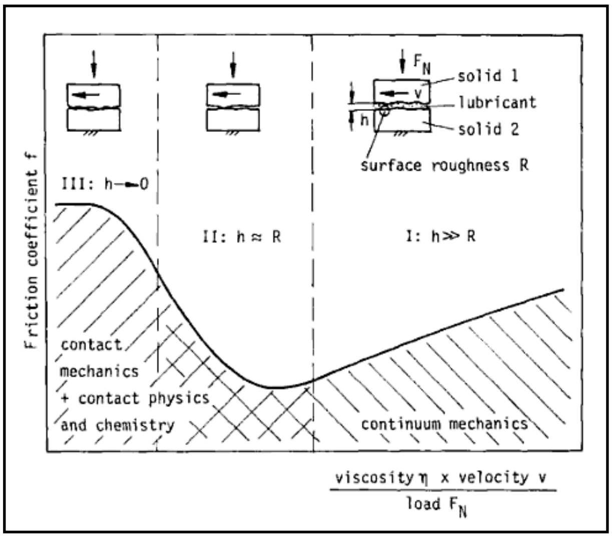

FIGURE 3-1: TYPICAL STRIBECK CURVE (CZICHOS 1978)

3.2.3 *ACCESSIBILITY*

The financial burden on stroke patients often means that those who would benefit most from intensive rehabilitation with a physical therapist are unable to afford it. Therefore this device should be able to be used in the home and require minimal setup and no direct supervision by a physical therapist. The device should also be cheap and rugged enough that stroke victims are able to purchase or hire the device from a hospital at a reasonable cost.

The device should also be as light and compact as possible if it is to be transported and used in the home. Simplicity of operation and an intuitive user interface are paramount to the successful adoption by stroke patients wishing for a viable alternative to face-to-face rehabilitation. It is anticipated that the only requirement for the patient to use the device will be a computer and internet connection, over which the therapist can monitor their progress and specify appropriate therapy routines.

3.2.4 *FORCE GENERATION*

Developing a force feedback system for the device is beyond the scope, financial limitations and time constraints of this study. The intention is to initially develop a passive wrist exercise device with the capacity for a force generation system to be implemented at a later time. Nevertheless, the requirements of a force feedback system will be briefly outlined as they will inevitable impact on the design of the passive device.

Important requirements of a force feedback system include:

- Low endpoint impedance and inertia to minimise force exerted by patient.
- Ability to actively counteract the force of gravity for passive movement.
- Smooth and natural force generation, similar to that of human therapy.
- Reasonable output torque to assist with movement, however significantly less than the maximum strength of the wrist and forearm to avoid injury.

The likely torque asserted by the force-feedback system is particularly important, as this will govern the forces on the device components. The maximum torque capable of being generated by the wrist and forearm is approximately 1.2 Nm in abduction/adduction and flexion/extension and 1.69 Nm in pronation/supination (Williams, Krebs & Hogan 2001). Naturally, the torque applied by a force-feedback system should be significantly less than these maximum strengths for safety. Future development of force generation hardware will be discussed further in Chapter 7.

3.3 Conceptual Designs

The following section briefly outlines three of the most promising initial design ideas developed during the brainstorming stage. These concepts will not be presented as fully developed designs but rather as simple 3D models or modifications of existing technology. Each will be critically assessed against the design requirements stated earlier in Section 3.2, in an attempt to eliminate any ungrounded personal preference towards one design or another.

3.3.1 Concept 1: 3-Link Platform

The three link platform configuration has been used in wrist rehabilitation devices before, one of which being the Rice-Wrist (O'Malley et al. 2006). This device actually encompassed the patient's upper and lower arm similar to an exoskeleton. In contrast, this concept has the device external to the patient so that the moveable platform still sits over the patient's wrist but the extensible links are positioned away from the arm rather than encompassing it. The design is best explained by the 3-dimensional model presented in Figure 3-2.

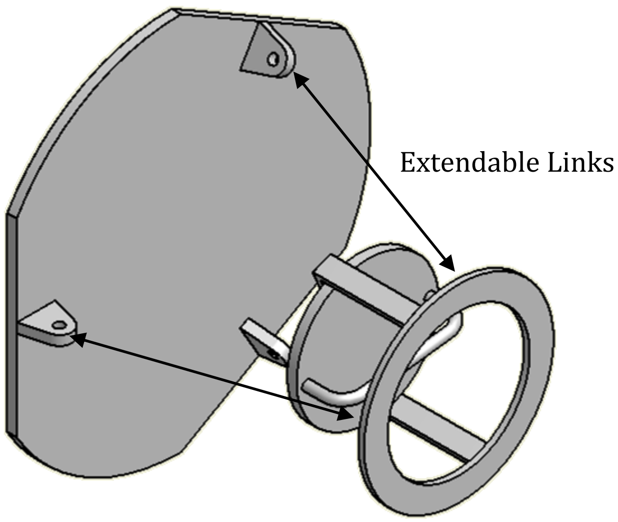

Figure 3-2: 3D representation of 3-link platform concept.

The patient's hand is placed through the moveable ring and grasps the attached handle. The wrist sits roughly in the centre of the ring and the forearm must be constrained by a fixed support such that only rotation is possible. Flexion/extension and abduction/adduction of the wrist cause the extendable links which connect the moveable platform to a static base plate to change length. The four degrees of freedom enabled by the extendable links are somewhat limited due to the geometry of the design.

The handle can also rotate within the moveable plate, accommodating rotation of the patient's forearm. This design would have a lower moment of inertia about the forearm rotation compared to the RICE-Wrist, which has this rotational freedom occurring at the base plate rather than the end-effector. The trade-off is a slight increase in weight at the end effector due to the required sensors and actuators.

The extendable links would require linear sensors such as sliding potentiometers to measure their lengths at any point in time. Similarly, linear actuators would be required to implement force generation. Both of these linear components are quite expensive and are beyond the budget of this project and most stroke patients. Alternatively, a rack and pinion arrangement could remove the need for linear components, instead allowing the use of less costly rotary potentiometers and motors. Again, the cost of purchasing or manufacturing rack and pinions is relatively high.

This is an eloquent design, however its development is likely to exceed the budget and time limitations of this study. A summary of the designs advantages and disadvantages are listed below:

Advantages:

- External design offers easier setup and less constriction on the patient compared to the Rice-Wrist.
- Singularity free over the majority of average wrist movement (O'Malley et al. 2006).
- Relatively simple to implement force-feedback.
- Lower inertia than the RICE-Wrist

Disadvantages:

- Limited range of movement due to limited length of the links and singularity constraints.
- Complexity of calculating actual wrist position from link lengths.
- Must overcome the force of gravity.
- Complicated design is not practical for in the home rehabilitation.
- Very expensive to manufacture extendable links.
- Requires four sensors to measure three degrees of freedom in the wrist and forearm.

3.3.2 Concept 2: Motion Controller

This design was partly inspired by the emergence of accelerometer based movement sensors in the gaming controller market. The success of these controllers such as Nintendo's Wii™ Remote, as depicted in Figure 3-3, appears to reflect their ability to accurately capture fluid human movement which in turn promotes intuitive and interactive game play. One can immediately imagine the application of such technology for movement therapy programs.

Figure 3-3: The Nintendo Wii™ remote (Nintendo 2009).

A small hand-held device similar to the Wii™ Remote could be constructed to measure the movement of the wrist and rotation of the forearm. The lower arm would have to be fully constrained to eliminate movement of the upper and lower arm, leaving only the wrist movements and forearm rotation free. The user would then exercise their wrist by moving the remote through a set pattern of orientations according to a visual stimulus.

The defining feature of this design is that position of the wrist is not being directly measured using a mechanical device. This means that the movement impedance is virtually non-existent as the inertia is extremely low and friction is eliminated. The effort exerted by the patient would be no greater than handling a typical television remote control. Range of movement is also completely unimpeded and the complex biomechanical structure of the wrist does not have to conform to typical mechanical joints.

Of course, there are drawbacks to this design, the most obvious being the inability to implement a force-feedback system. Any haptic feedback to the user would be limited to vibration or 'rumbling' of the controller which is pointless in terms of rehabilitative value. There is also the challenge of determining absolute position of the wrist without having any direct mechanical interface. Some possible options for position sensing are:

- Accelerometers or gyroscopes can measure tilt and acceleration of the device.
- Optical sensors such as infrared emitters and receivers could be used to determine the position of the device.
- A machine vision approach could be taken with multiple cameras capturing the position of the remote.

It soon becomes apparent that the required sensors and associated hardware for this design may well exceed the project's cost restrictions. One could also argue that the development of a new motion controller is somewhat unoriginal and unnecessary, as similar devices already exist on the market. Adaption of existing products such as the Wii™ Remote and the development of rehabilitation console games could probably achieve the same result.

Advantages:

- Minimal inertia for a lightweight remote.
- Frictionless operation.
- Limitless degrees of freedom, hence all wrist movement can be captured.
- Unique and intuitive movement therapy.
- Very accessible for in the home use.

Disadvantages:

- No provision for force feedback implementation.
- Complexity of determining absolute position of the wrist.
- Expensive sensors required.
- Similar designs already on the market.

3.3.3 Concept 3: External Cardan Joint

This solution exploits the wrist joint's approximation to a Cardan joint, in that it has two degrees of rotation about intersecting perpendicular axes. The design consists of a ring which pivots horizontally on a fixed base fork. Another fork pivots vertically on the ring and houses a rotating handle which is gripped by the hand. A 3D representation of the device is shown in Figure 3-4.

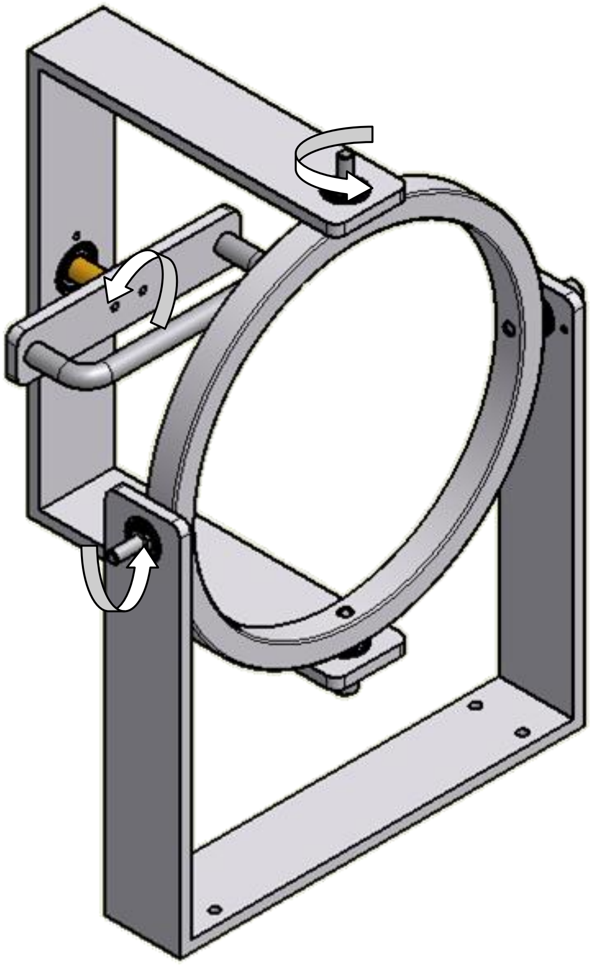

Figure 3-4: External Cardan joint concept.

Assuming the orientation of the handle is of that shown in Figure 3-4, flexion and extension is measured about the horizontal ring pivot. Similarly, radio-ulnar deviation is captured around the vertical axis. This straightforward design allows both of these movements to occur simultaneously. Rotation of the forearm is accommodated by the handle which is free to turn about an axis intersecting the centre of the ring. A forearm support will be used in conjunction with the device to restrict the forearm from any movement other than that of rotation.

The orientation of the handle inevitably changes the relationship between the extent of individual wrist motions and the rotation angles measured about the horizontal and vertical axes. However, a basic trigonometric relationship can be established so that the degree of abduction/abduction and flexion/extension can be calculated very easily from the raw rotation angles. Being able to establish the absolute position of the wrist at any point in time is one of the greatest advantages of this design.

The addition of force generating hardware is also well catered for in this simple design, although restricted space may result in decreased range of movement. Varying amounts of torque can be applied to each of the axes of rotation to drive the wrist towards a desired position, without the difficulties of singularities or complex kinematic relationships. An obvious drawback of the concept, as a passive system, is the torque generated by gravity about the horizontal axis. This torque would have to be overcome by a counteracting force if the device was to be truly passive.

A summary of the Cardan joint design's strengths and weaknesses is given below:

Advantages:

- High range of movement possible.
- Singularity free kinematics in the range of movement required.
- Combination of wrist movements can be captured simultaneously.
- Simple movement capture from the three axes of rotation.
- Low cost design.
- Simple to manufacture.
- Force-feedback would be easy to implement.
- Original and intuitive design.

Disadvantages:

- Cardan joint approximation of the wrist is not perfect.
- Force of gravity must be overcome for rotation about the horizontal axis.
- Limited space for force feedback actuators.
- Risk of pinching from moving parts.

3.4 Design Evaluation

All of the concepts have been considered carefully, and their strengths and weaknesses identified. Choice of the best design simply depends on how well each concept satisfies the functional requirements that have been developed.

Concept 1, the three link platform, satisfies most of the criteria very well including an acceptable range of movement and ability to implement force feedback. Its greatest drawback however is the complexity of its mechanics and kinematics. The manufacture of linear slides or rack and pinion pairs was considered too expensive for the budget of this project and naturally not affordable for purchase by stroke patients under financial stress. This concept design would be more suitable for the development of a rehabilitation system which would be purchased and based in a hospital or rehabilitation centre.

Concept 2, the motion controller, is an intuitive and creative idea which, by looking at similar products such as the Wii™ Remote, should be quite affordable for in the home rehabilitation. Although the concept is more of an adaption of existing technology rather than an original design, the use of motion control in gaming consoles presents an exciting opportunity for the development of rehabilitation games. This concept was effectively dismissed however, by the fact that the addition of force generating hardware would be impossible to implement. Hence, the concept is unsuitable for development in this study, although it has potential to revolutionise passive movement therapy.

The external Cardan joint design, presented as Concept 3, excels in its simplicity of operation and intuitive mechanics. By emulating the wrist joint in an exoskeleton type design, the device is successfully able to capture a wide and complex range of wrist movement without singularities or complex kinematic relationships. The implementation of force-feedback is also well catered for because all movement is measured directly on three axes of rotation which can be driven by actuators to create an active device.

Concept 3 presents the best solution for further development into a prototype and further discussion in this Chapter is related to this choice of design.

3.5 Movement Capture

In order to evaluate patient condition and improvement, a wrist therapy device must be able to accurately record movement with reasonable accuracy, precision and repeatability. As movement is simply change in position over time, the absolute position of the device must be measured repeatedly at small time intervals. There are a number of different ways that this position sensing can be achieved. This section will explore the most viable solutions.

3.5.1 Requirements

Movement capture involves the use of position sensors and data acquisition hardware which periodically reads them. The following criteria were developed for the overall movement capture system. Some will impose direct requirements on the position sensors and others will govern the choice of data acquisition hardware. The following requirements have been determined:

- Ability to calculate absolute position of the wrist.
- System should be low cost (<$100).
- Voltage supply is limited to 5V and current draw should not exceed that of a typical USB supply (700mA).
- High compatibility with computer systems.
- Ease of component replacement is expected.
- Resolution should be no more than 1°.
- Linearity of output should be high.
- Movement should be sampled at a rate greater than that of human persistence of vision (>24Hz).

3.5.2 *Sensors*

There are a number of different ways position of the wrist can be measured using the mechanical design chosen in section 3.4. The most obvious is to measure the degree of travel on each axis of freedom with a rotary position transducer. Some of these transducers will be looked at in this section along with other ingenious solutions.

3.5.2.1 Potentiometer

The humble potentiometer is perhaps the simplest of devices to measure rotary position. This three terminal device has a sliding contact connected to the rotary input shaft and forms a variable voltage divider. Hence, when a steady voltage is applied across the fixed contact terminals, the voltage measured on the wiper terminal is proportional to the rotary position of the shaft, effectively making the potentiometer a position transducer.

Potentiometers either have a linear of logarithmic relationship between the shaft position and the resistance, depending on their intended application. They also come in single turn types with a rotation angle of 270° to 340° and multi-turn types which range from 2 to 20 turns. Potentiometers are rated by the resistance across their fixed contacts, number of turns, precision, linearity and type of resistive material used.

For the purpose of measuring rotational position, a linear type potentiometer is appropriate. Regular potentiometers, like that shown in Figure 3-5, can be purchased for less than $2. However, a long-life, highly linear, precision potentiometer is likely to cost more than $20 (RS Online 2009).

FIGURE 3-5: A TYPICAL POTENTIOMETER (RS ONLINE 2009).

3.5.2.2 Rotary Encoder

The rotary encoder is split into two different types, the incremental encoder and the absolute encoder, both of which convert mechanical position of a shaft into a digital output. Rotary encoders either use mechanical switches or optical sensors to drive their outputs. Optical types are typically adopted for high speed applications to overcome the problems of switch bouncing and mechanical contact wear.

Incremental encoders output two, out of phase square waves, from which speed and direction of travel can be calculated. Figure 3-6 shows the state of these A and B outputs at four signal edge transitions, demonstrating how direction of rotation can be established. The signal traces show that clockwise rotation gives the gray code outputs 00→10→11→01 and anti-clockwise rotation has outputs 10→00→01→11. These transitions are gray code because only one input changes at a time, reducing read errors.

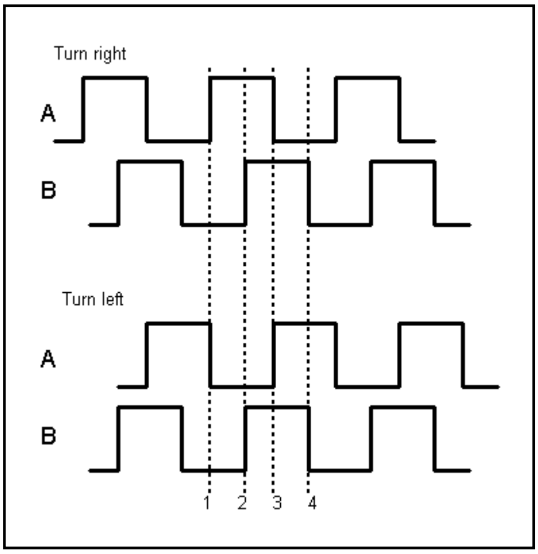

FIGURE 3-6: TYPICAL OUTPUT SIGNALS FROM AN INCREMENTAL ENCODER (HISTAND & ALCIATORE 1999).

A limitation of the incremental encoder is that calculating absolute position requires calibration to a datum angle every time the signal count is reset. Excessive speed may also generate invalid readings, e.g. 00→11, in which case the direction of travel is unable to be ascertained. Precision incremental encoders are also very expensive (>$100 for 256 pulses per revolution), hence the use of cheaper, lower resolution encoders would require the addition of gears or pulleys to increase the number of pulses per revolution.

Absolute encoders overcome some of these problems and have the advantage of outputting a unique binary code for each distinct shaft angle. Optical types use a disk of transparent and opaque areas, as shown in Figure 3-7, and photo-detectors output a binary pattern corresponding to the shaft's position. Resolution of the encoder is therefore determined by the number of digital outputs.

For example, a three bit absolute encoder has $2^3 = 8$ possible binary outputs, which means the shaft position has eight distinct regions of 45° each. An absolute encoder capable of the required precision of <2° would cost upwards of $300 (RS Online 2009).

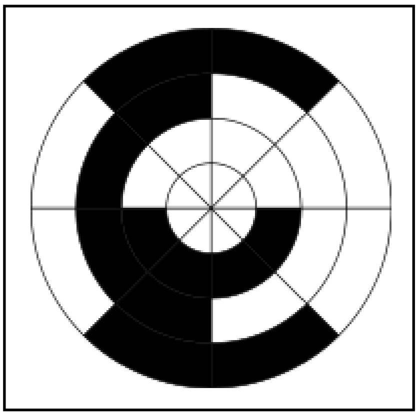

FIGURE 3-7: THE OPTICAL INTERFERENCE DISK WITHIN A 3-BIT ABSOLUTE ENCODER (HISTAND & ALCIATORE 1999).

The distinction between absolute and incremental encoders is sometimes blurred. An interesting compromise is an incremental encoder which also outputs a datum pulse at a set point in its rotation. By initially finding this point during calibration, all rotation can be found relative to a known and mechanically adjustable datum plane.

3.5.2.3 Hall Effect Sensor

A Hall Effect sensor outputs an analogue voltage proportional to the strength of the magnetic field passing through it. They can be used to measure rotational position by placing the sensor within a magnetic field, as shown in Figure 3-8. The angular position of the sensor with respect to the direction of magnetic flux can be determined from the magnitude of the analogue output. A device with two Hall Effect chips positioned perpendicular to each other is capable of measuring angle over a full 360° range.

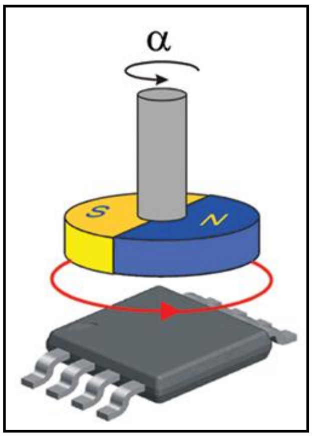

FIGURE 3-8: HALL EFFECT SENSOR IN POSITION SENSING APPLICATION (MELEXIS 2009).

These dual axis chips have two outputs, from which angular position can determined. When the magnet is rotating, the analogue voltages are proportional to the magnetic flux densities in their respective axis and appear sine waves in quadrature, as depicted in Figure 3-9. By taking the tangent of the ratio of these outputs, the angular position of the shaft holding the magnet can be calculated.

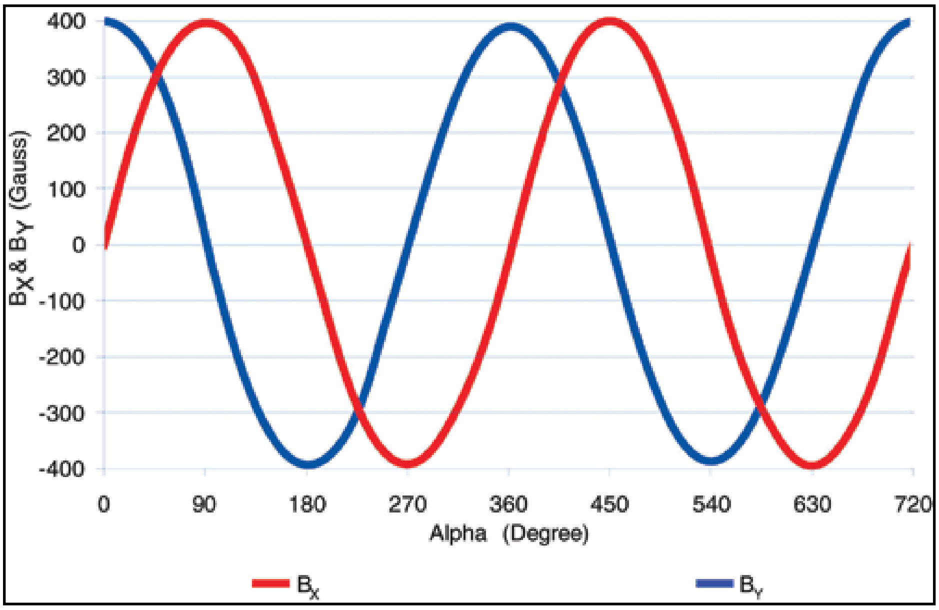

FIGURE 3-9: SINUSOIDAL WAVE OUTPUTS FROM A HALL EFFECT SENSOR (MELEXIS 2009).

Dual axis Hall Effect sensors are not cheap, in fact the Melexis MLX90316, which is specifically designed for position sensing, costs approximately $50. The sensors also require quite precise placement within the magnetic field, as any eccentricity may cause erroneous readings. Another concern is that the eventual addition of force generation hardware is likely to use electric motors which can produce significant magnetic fields. These may disrupt the magnetic flux from the permanent magnets and influence the sensitive outputs of the Hall Effect sensors.

3.5.2.4 Machine Vision

A rather ingenious solution involves the use of cheap cameras, such as webcams, to capture the position of certain points on the device. These points may be bright light emitting diodes or reflective spots which provide a contrasting point that can be found using some image processing software. Position of the device could be determined by placing the cameras in such a way that the position of the datum points is indicative of that of the device.

For the design that has been chosen, a camera would be placed vertically above the device such that the rotation about the vertical axis could be measured. If two LEDs were placed on each end of the top side of the fork, this camera could also determine the rotation of the fork about the horizontal axis by measuring the distance between the two points. Similarly, a camera looking at the back of the device could detect forearm rotation and whether the fork has been tilted upwards or downwards.

This solution would not be particularly expensive, as webcams are readily available for less than $50. However, there are some inherent disadvantages. Setup of the cameras would have to be fairly precise and not something that would be particularly simple to achieve in the home. It would also be prone to poor lighting conditions and other interference by the patient, which may impede operation. Calculation of wrist position would also be significantly more complicated compared to simply measuring the rotary position of each rotational degree of freedom.

3.5.2.5 Accelerometer

There are a number of analogue and digital devices on the market which can measure the acceleration of gravity over 2 or more axes in order to determine tilt of the chip. If a three axes chip is used, pitch, roll and yaw can be measured from the three analogue outputs. Hence, by placing the chip at the handle of the device, its absolute position can be calculated from the measured acceleration on each axis. These raw values could be converted to the actual angles of wrist movement, using the distance of the chip from the known axis of rotation.

Effectively, this could be a one-chip solution, or alternatively several dual axis or single axis chips may be utilised. One potential problem would be that external acceleration of the device by the patient will be included in the outputs of the sensor, so that the actual tilt of the device will only be accurate when it is static. One could assume however that the acceleration of the handle will probably be insignificant compared to that of gravity.

3.5.3 *Data Acquisition*

Position transducers are not particularly useful unless their outputs can be captured and manipulated to create meaningful data. Given the scope of the project, an embedded microcontroller will be used in this project to perform the data acquisition from the sensors and communicate with the computer. This section will outline some required features of an embedded microcontroller and development board so that a suitable choice selection of hardware can be made.

3.5.3.1 User Interface

Data acquisition hardware must be able to display meaningful results to the user and allow them to manipulate operation of the program. This typically involves a visual display such as a character LCD, on which immediate results can be displayed for user information and debugging purposes. Push buttons on the development board should also allow the user to scroll through menus or change how the data is displayed on the screen.

3.5.3.2 Analogue to Digital Conversion

Many of the sensors discussed earlier do not directly output digital data, rather most produce one or more analogue voltages. For example, a potentiometer provides an analogue voltage at its wiper terminal proportional to its shaft position when a fixed voltage is applied across its fixed contacts. Computer software requires this analogue data to be converted into a digital number before it can be useful.

An analogue to digital converter (ADC) is a standalone chip or a built in module of a microcontroller which fulfils this function. There are a number of factors to consider when choosing a microcontroller with ADC capability. These include the number of channels, minimum conversion time and resolution. The required number of channels will depend on the choice of position sensor and the number of analogue signals to be converted. Assuming one analogue output for each axis of rotation, a microcontroller with at least three ADC channels will be required.

Conversion time for an ADC is the time it takes to convert an analogue signal at full resolution and maximum accuracy. The limiting factor to consider here is that the position sensor signals must be sampled at a rate faster than human persistence of vision so that smooth movement can be displayed to the patient. A refresh rate of 24Hz is recommended for a flicker free display and the aim is to sample the sensors at a considerably higher rate of 50Hz or every 20ms. A typical ADC can perform a conversion in under 50ns, so this requirement will not limit the choice of microcontroller.

Resolution of the ADC is a critical consideration, as this will quite often be the limiting factor. A high quality potentiometer, for example, has a virtually infinite resolution, so the precision of position measurement depends solely on the ADC resolution. The required precision of ±1° means that if the full analogue voltage range of the sensor occurs over 360°, the required resolution of the ADC must be greater than 360.

Low cost microcontrollers typically include an 8-bit or 10-bit resolution ADC module, which correspond to resolutions of 256 and 1024 respectively. Therefore a 10-bit resolution ADC would be capable of a significantly higher precision than that required. This can be calculated as shown in equation 3.1 below:

$$Precision = \frac{360°}{1024} = 0.35° \qquad (3.1)$$

3.5.3.3 Data Transmission

The development board and embedded microcontroller must be capable of transmitting the relevant position data to computer software. Data must be transferred through a serial port or USB connection depending on the functionality of the development board. The microcontroller would benefit from having a built in module for serial transmission, to simplify the software development.

3.5.4 Design Choice

Potentiometers present the best characteristics for position capture in this design. Their simplicity of implementation and direct connection to each axis of rotation will make the calculation of wrist position very straightforward. Another advantage of using potentiometers is that absolute positions can be determined from their analogue voltage outputs. Sensors which output an incremental signal are prone to error over time and constantly require calibration. Precision potentiometers have high linearity and virtually infinite resolutions, making them ideal as rotational transducers on this device.

A development board with an embedded microcontroller will be used for data acquisition, processing and communication with the computer. The board must have an LCD display and buttons for user input. The specific requirements of the microcontrollers are that it contains a 10-bit ADC module with at least 3 channels and the ability to transfer data serially.

3.6 Conclusion

A wrist rehabilitation device should measure the motions of wrist flexion/extension, abduction/adduction and also forearm supination/pronation. The minimum range of motion of the device should be no less than that required to adequately perform activities of daily living. Friction and inertia should be minimised to reduce the physical requirement to operate the device. A passive device will be developed initially with the intention and design accommodations to implement force feedback at a later stage.

A number of concepts were developed and critically analysed against specified design criteria. The chosen design successfully captures the targeted movements by placing a Cardan joint over the wrist and allowing rotation of the forearm at the end effector. This solution is incredibly simplistic in nature, yet succeeds in emulating the natural movement of the wrist. Each of the device's axes of rotation corresponds directly to a raw motion of the wrist or forearm which reduces the complexity of determining actual joint positions.

Methods of motion capture were presented, including a number of possible sensors with their inherent advantages and disadvantages. Potentiometers were deemed to be the most suitable choice for rotary position sensing due to their simplicity of operation, virtually infinite resolution and availability. Data acquisition hardware was also discussed and specific requirements, such as analogue to digital conversion, were identified.

Chapter 4 PROTOTYPE DESIGN

4.1 INTRODUCTION

This chapter will document the detailed development of the prototype device leading on from the concept analysed and chosen in Chapter 3, into a fully functional prototype. In approaching the design of the prototype, a holistic mechatronic viewpoint was embraced in an attempt to effectively and efficiently integrate the mechanical and electronic aspects of the design. This design philosophy has resulted in a prototype which meets and exceeds the requirements set out in Chapter 3.

Important features of the mechanical structure of the device will be identified and justification of design choices will be made. The electronic hardware will also be examined with detailed explanations and supporting circuit schematics. Integration of the mechanical device, sensors and data acquisition must be carefully orchestrated so that all of the design requirements are satisfied.

4.2 MECHANICAL STRUCTURE

Design of the mechanical structure was carried out with the assistance of parametric solid modelling software called *Autodesk Inventor Professional 2009*. The development of a 3D model of the device with fully operational kinematic relationships made it possible to virtually test its mechanical performance and range of motion on screen before manufacturing an actual prototype. Parametric 3D modelling software permitted an iterative process of design, allowing the continual adjustment of dimensions and constraints until an ideal structure was obtained.

Ease and affordability of manufacture were key considerations during the design and development. With this in mind, all materials and components specified in the workshop drawings were standard sizes and readily available. Another important consideration was weight minimisation to reduce inertia. Hence, most of the components have been manufactured out of aluminium which has sufficient rigidity and strength for this application.

Before delving into an in depth study of the individual design features, an overview of the final prototype 3D model can be seen in Figure 4-1 and Figure 4-2. All detailed drawings of the device can be found in Appendix B.

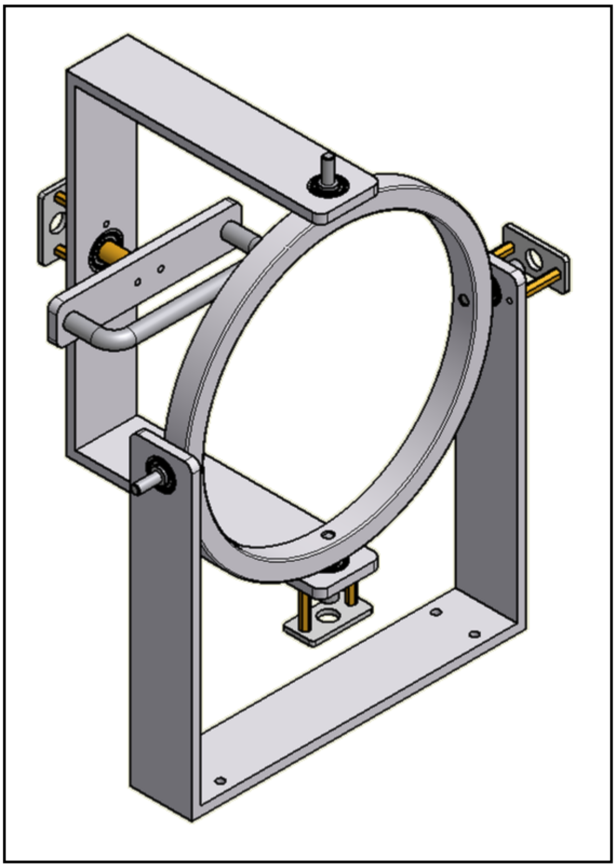

FIGURE 4-1: FRONT ISOMETRIC VIEW OF THE PROTOTYPE 3D MODEL.

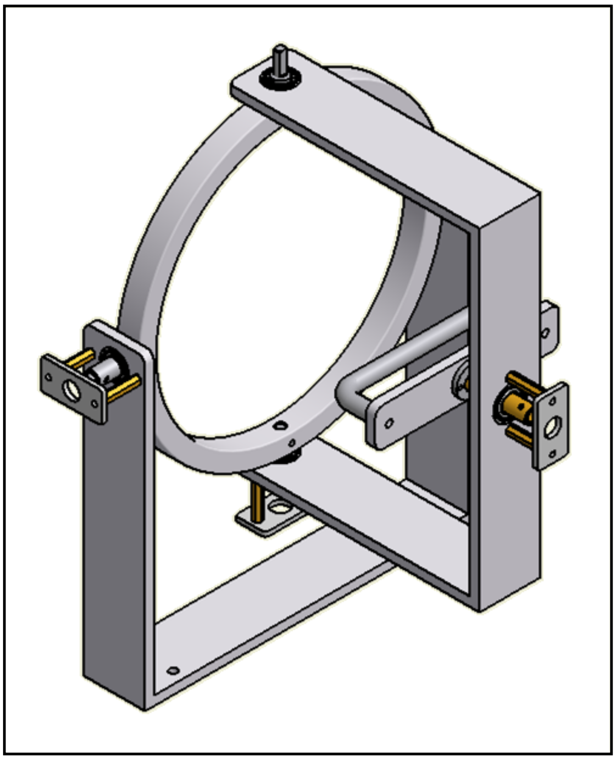

FIGURE 4-2: BACK ISOMETRIC VIEW OF THE PROTOTYPE 3D MODEL.

4.2.1 Components

The base fork consists of a bent piece of 40 x 6mm aluminium flat bar as shown in Figure 4-3. The width of material was chosen to allow two 19mm diameter holes which house the ball bearing to be drilled at the top of the fork. Holes were also drilled in the base so that the fork can be rigidly attached to a platform. To accommodate the wide range of movement desired, the forks were made approximately 200mm apart and 185mm from the base to the bearing centres.

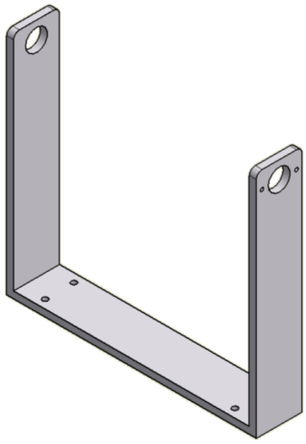

Figure 4-3: Base fork 3D model.

The pivot fork in Figure 4-4 is almost identical to the base fork, although the lengths of the forks are slightly shorter at 150mm from base to pivot. This length was chosen as a compromise between device range of movement and its ability to accommodate larger hands. An extra 22mm diameter hole in the base of the fork accommodates the bearing about which the handle pivots. Two 3mm holes are drilled each side of the bearing holes for the mounting of the position sensors.

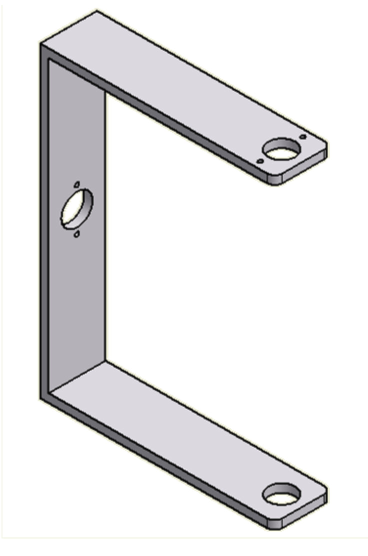

Figure 4-4: Pivot fork 3D model.

The cross ring effectively joins the pivot fork to the base plate and is manufactured from a 15mm long piece of 200mm O.D. aluminium pipe which is a standard section. The inner diameter of 176mm is large enough to allow the hand to pass through and accommodate the wrist. Four, equally spaced pivot holes are drilled radially through the middle of the ring. These holes house steel pivots which connect the ring to the base fork and pivot fork. Threaded M3 holes on the flat face of the ring allow grub screws to hold the steel pivots firmly in place as any slippage is undesirable.

FIGURE 4-5: CROSS RING 3D MODEL.

Each pivoting axis on the cross ring houses a drive shaft on one side and a sensor mount shaft on the opposite side. The drive shaft, as shown in Figure 4-6, was designed to simplify the addition of force feedback hardware at a later stage. This shaft runs through the bearing and is fixed to the cross ring by a grub screw which contacts the flat. The input side has a 6mm diameter D shaped profile along its entire length so that gears or pulleys can be firmly attached without slippage. The shaft is made of 10mm bright steel round for strength and resistance to corrosion.

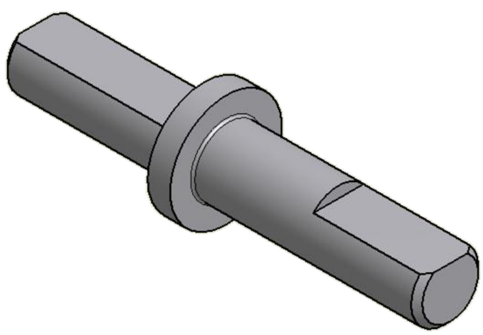

FIGURE 4-6: DRIVE SHAFT 3D MODEL

The shaft which houses the position sensors is shown in Figure 4-7. The shaft runs in the bearing, with the male side secured within the cross ring by a grub screw. A hole on the other side closely matches the size of the position sensor shaft which is locked by a 3mm grub screw. This sensor mount shaft is also manufactured from 10mm bright steel round and feature a flat edge for positive locking in the cross ring.

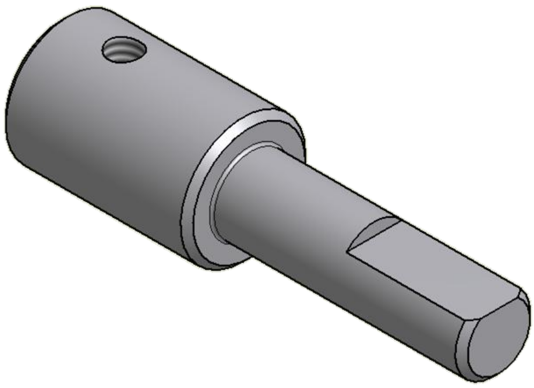

FIGURE 4-7: SENSOR MOUNT SHAFT 3D MODEL.

The position sensors are bush mounted types and require a panel to be mounted on. This panel, shown in Figure 4-8, is made from 20 x 3mm aluminium flat and is 40mm long to match the width of the forks. To give the panel a degree of compliance, it is separated from the forks by 25mm plastic spacers, attached with screws. The compliance afforded to the panel allows the inevitable slight misalignment of the sensor shaft in the mount shaft. An 11mm hole in the centre allows the threaded bush of the sensor to pass through and be fixed with accompanying nut and washer.

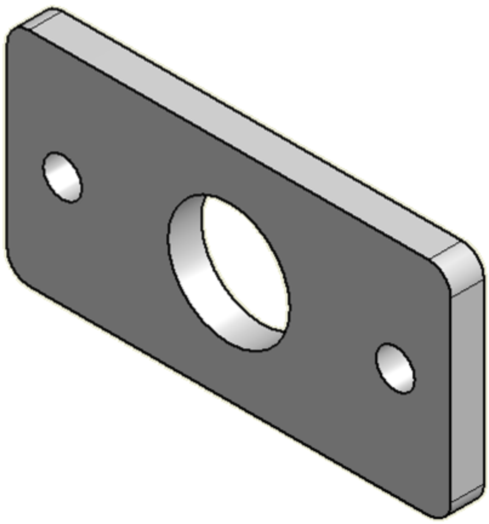

FIGURE 4-8: SENSOR MOUNT PANEL 3D MODEL.

The bearing on the base of the pivot fork has a sleeve pressed into it as shown in Figure 4-9. This sleeve accepts the position sensor shaft in one end and the handle shaft in the other. Two grub screws are used to secure these tightly in the sleeve which has an outer diameter of 10mm and inner diameter of 6mm to suit the shafts.

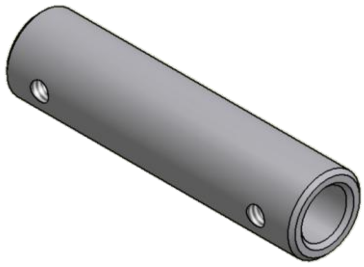

FIGURE 4-9: BEARING SLEEVE 3D MODEL.

A handle shaft, as shown in Figure 4-10, slides within the bearing sleeve for adjustment of distance from the handle to the cardan joint. This adjustment allows hands of different sizes to comfortably use the device and supports handle to wrist lengths of 60 to 90mm. The shaft has a face plate with tapped holes to accept the handle mounting plate.

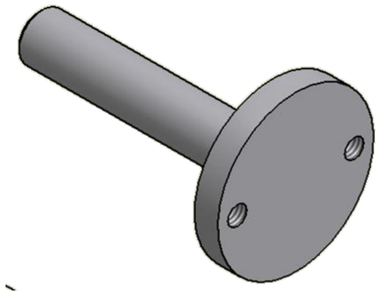

FIGURE 4-10: HANDLE SHAFT 3D MODEL.

The end effector of the device is a simple stainless steel cupboard handle attached to an aluminium base plate as shown in Figure 4-11. The base plate is manufactured from 25 x 6mm aluminium flat and accepts a handle with a 102mm centre to centre distance.

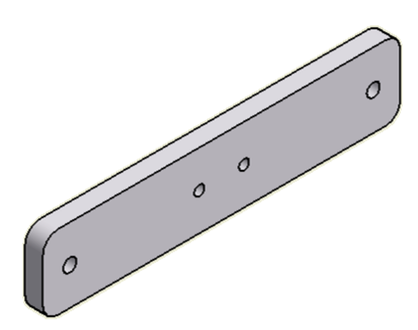

FIGURE 4-11: HANDLE MOUNT 3D MODEL.

4.2.2 *BEARING SELECTION*

As discussed in Chapter 3, reduction of friction in the mechanical joints is an imperative requirement. Ball bearings have been adopted at all of the axes of rotation as they are effective at reducing friction at very low speeds. The selection of specific bearings depends on a number of factors including radial load, axial load and shaft diameter.

To determine the maximum radial and axial loads likely to be experienced by the bearings, the forces at the pivots of the cross link must be examined. As a passive device, the force on any of these points will be no more than that opposing the acceleration of the wrist. The load on the bearings therefore will be negligible. However, the implementation of force feedback and the likely forces that will be generated must be considered.

Assuming the force generated is opposing the maximum capable torque of the wrist movements, the axial and radial forces on the bearing can be calculated. The wrist is capable of 1.2 Nm torque in both the flexion/extension and adduction/abduction axes, as stated in Chapter 3. The minimum distance d between the Cardan joint and the handle centre of the device is approximately 80mm. Therefore, when the torque of the wrist T acts on the end effector, the reaction force at the bearings can be calculated as shown in equation 4.1.

$$F = \frac{T}{d} = \frac{1.4Nm}{0.08m} = 17.5N \qquad (4.1)$$

This force is transmitted radially between the two bearings aligned about the axis of torque and axially on the bearings perpendicular to these. Bearings were selected from the SKF bearing catalogue (2009) to suit the two 6mm and one 10mm shafts. The radial static load capacity of the 262-2RZ bearings chosen is 950N, significantly greater than the expected load. A maximum axial load of 17.5 N is also acceptable for this type of ball bearing.

4.2.3 *Assembly*

Before briefly describing the assembly process, the reader should familiarise themselves with the parts in the exploded view shown in Figure 4-12. The ballooned numbers are reference each of the parts given in Table 4-1.

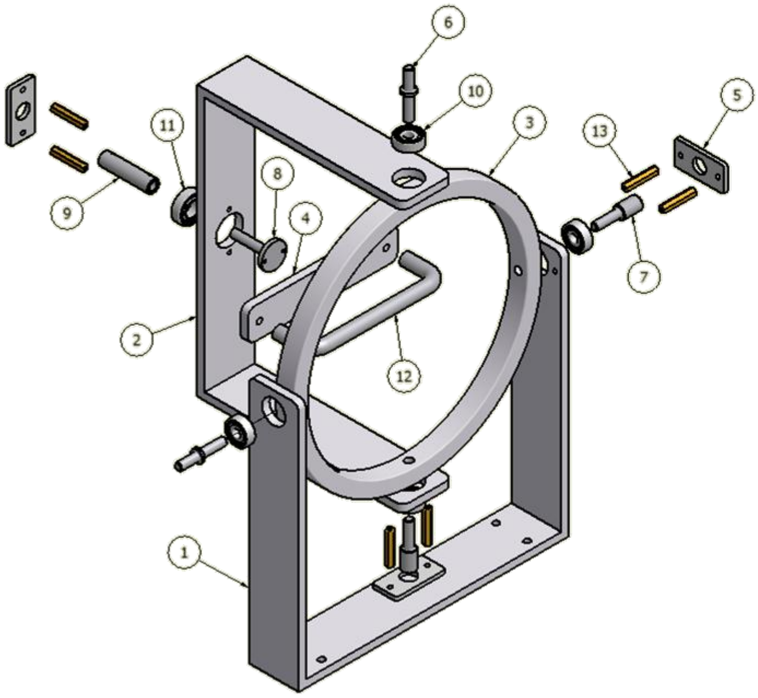

Figure 4-12: Exploded view of the prototype 3D model.

Table 4-1: Prototype parts list.

Item	Part	Material
1	Base Fork	40 x 6 Alum. Flat
2	Pivot Fork	40 x 6 Alum. Flat
3	Cross Ring	200 O.D. x 12 w. Alum. Tube
4	Handle Mount	25 x 6 Alum. Flat
5	Sensor Mount Panel	20 x 3 Alum. Flat
6	Drive Shaft	10mm Bright Round
7	Sensor Mount Shaft	10mm Bright Round
8	Handle Shaft	20mm Bright Round
9	Bearing Sleeve	10mm Bright Round
10	Bearing (626-2RS)	Purchased
11	Bearing (608-2RS)	Purchased
12	Handle	Stainless Steel
13	Flexible 25mm Spacer	Plastic

All of the bearings are press fit into their respective holes in the forks, and the surrounding material pined to keep them from moving axially. This form of support was considered adequate because of the low axial forces expected. The base fork is fixed to a 500 x 500mm melamine coated particle board base plate which will also hold the support for the forearm. Four wood screws secure the base fork to the board which has rubberised feet to avoid slippage on a table.

Next, the cross ring is placed in position and the drive shaft is pushed through the bearing and into the pivot hole so that the flat edge is lined up with the grub screw. A position sensor mount shaft similarly placed through the opposite bearing so that the ring is fully supported on both sides. The cross ring is roughly centred between the forks and the grub screws are fastened such that there is no axial play in the pivot. The same procedure is repeated to attach the pivot fork to the cross ring.

The bearing sleeve is press fit into the handle pivot bearing and the handle shaft can slide into the forward facing side of this sleeve. A grub screw in the bearing sleeve fixes the shaft at the desired length, depending on the size of the patient's wrist. The stainless steel handle should be bolted onto the handle mount before fixing this to the shaft with set screws. The handle should now rotate freely in the bearing without any axial play.

All of the flexible spacers can now be fitted with self-tapping screws and the panel mounts attached with screws also. The position sensors are then mounted tightly on the panels with their shafts fixed by grub screws in the mounting shafts. Care should be taken not to over tighten the grub screws or else the fine threads may be damaged, particularly those tapped in aluminium. A photograph of the positions sensor mounted on the device is shown in Figure 4-13.

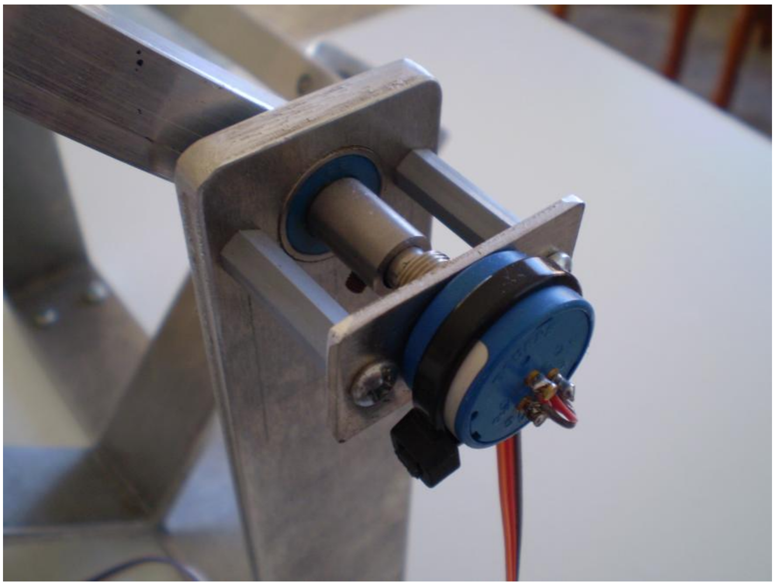

FIGURE 4-13: POSITION SENSOR MOUNTED ON THE DEVICE.

4.3 ELECTRONIC HARDWARE

The electronic hardware consists of position sensors, microcontroller, development board and interface circuitry. The choice of components for each of these will be briefly analysed in this section.

4.3.1 SENSORS

Potentiometers were deemed to be the best choice of rotational position transducer. Their simplicity of implementation, low cost and virtually infinite resolution made them ideal for use on the device. For this application, linearity, precision and high durability are also very important factors. The largest required rotational freedom of the device is that of forearm rotation, which requires 140° of motion. All of the potentiometers could therefore be single turn types for maximum resolution.

The sensors used on the device are Bourns 6639 Precision Potentiometers, as shown in Figure 4-14, which are bushing mounted and have the following features:

- 340° electrical angle without mechanical stops.
- Essentially infinite resolution.
- Highly linear (±2%).
- High rotational life (10 million rotations).
- Exceptional quality and rugged construction.

A resistance of 10kΩ was chosen to minimise current draw, as it is anticipated that a USB supply will be used to power the device.

FIGURE 4-14: BOURNS 6639 PRECISION POTENTIOMETER (RS ONLINE 2009).

4.3.2 MICROCONTROLLER

There are a broad range of embedded microcontrollers on the market today, the most prominent of which are the ATMEL, ARM and PIC range of chips. Choice of chip architecture not only depended on the functional requirement of the data acquisition but was also influenced by previous experience with Microchip's PIC range of microcontrollers. The requirements of the device, as outlined in Chapter 3 were best fulfilled by the PIC16F877A microcontroller as pictured in Figure 4-15, which has the following features:

- Maximum clock speed of 20MHz.
- 33 Input/output (IO) pins
- 10-bit, 8 channel Analogue to Digital Converter (ADC).
- 8K flash program memory.
- 256 bytes of EEPROM data memory.
- Two 8-bit and one 16-bit timer.
- Universal Synchronous Asynchronous Receiver Transmitter (USART) module.
- Two pulse width modulation (PWM) modules.

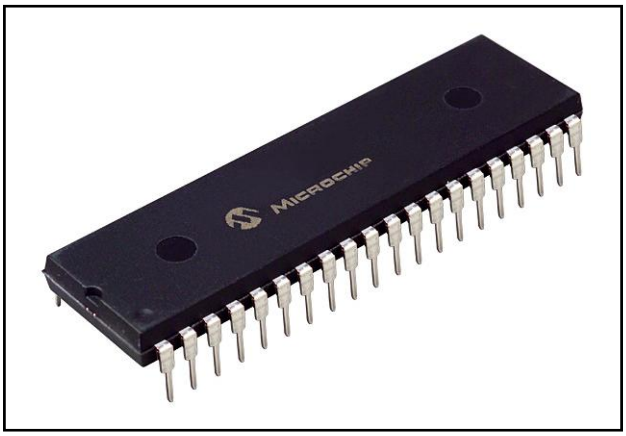

FIGURE 4-15: MICROCHIP'S PIC16F877A MICROCONTROLLER.

Features such as the 20MHz clock speed, IO capability, memory capacity and ADC specifications satisfy the requirements outlined in Chapter 3. The 16F877A has many additional features and IO functionality which will not be utilised in the development of a passive device. This leaves significant room for expansion and it is anticipated that features such as the PWM modules would be appreciated when a force feedback system is developed at a later stage.

4.3.3 Development Board

Choice of a development platform was primarily governed by the selection of the microcontroller chip. A suitable development board based around the PIC16F877A microcontroller is the PIC-MT-USB by Olimex as shown in Figure 4-16. This board has a number of features which make it an attractive solution for data acquisition and display. These include:

- Two 10 pin expansion headers for unused ports.
- 16 general purpose IO pins accessible.
- 20 MHz crystal on board.
- Serial communication via RS232→USB embedded integrated circuit.
- In Circuit Serial Programming (ICSP) capability.
- Alphanumeric display 2x16 LCD with backlight.
- Two push buttons, hardware debounced.
- Bi-colour led.
- Power supply taken from a computer USB port.

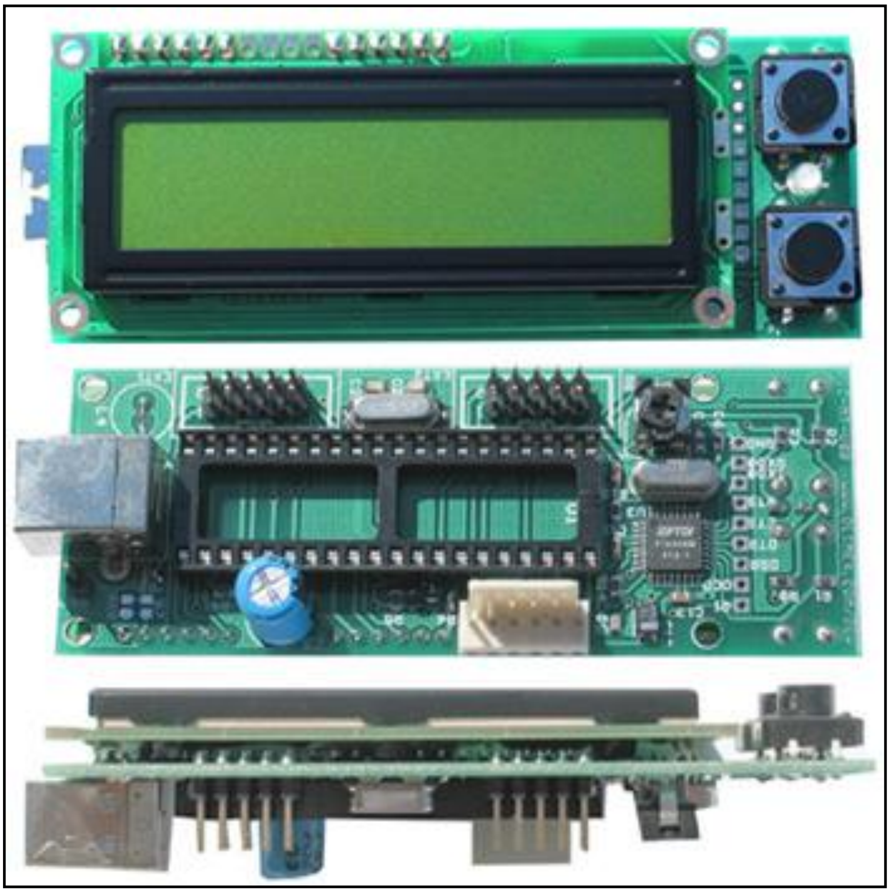

Figure 4-16: Olimex PIC-MT-USB development board.

4.3.4 *Interface*

The potentiometers are connected to the development board through pins RA0, RA1 and RA3 from expansion port EXT2 as shown in Figure 4-17. Power and ground are sourced from expansion port EXT1, and are used to apply a 5V voltage across each of the potentiometers.

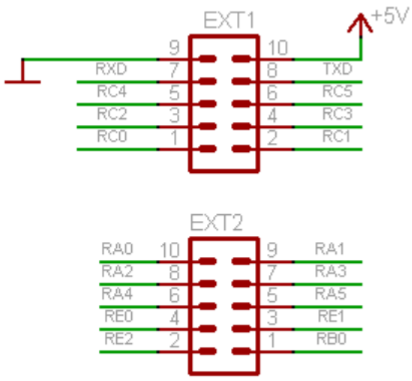

Figure 4-17: Development board expansion ports (Olimex 2008).

A simple interface circuit, as shown in Figure 4-18, was constructed on a prototype printed circuit board, photographed in Figure 4-19. This consists of a low pass filter on each potentiometer output to eliminate any high frequency interference picked up on the ribbon cable connecting the device to the interface board. The filtered output voltages of each potentiometer are connected to three ADC channels on the microcontroller.

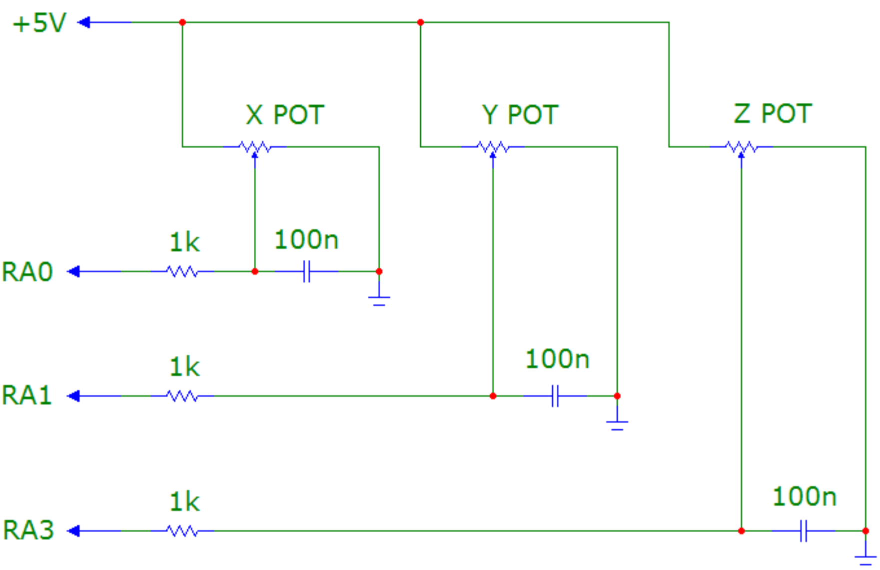

Figure 4-18: Potentiometer interface schematic.

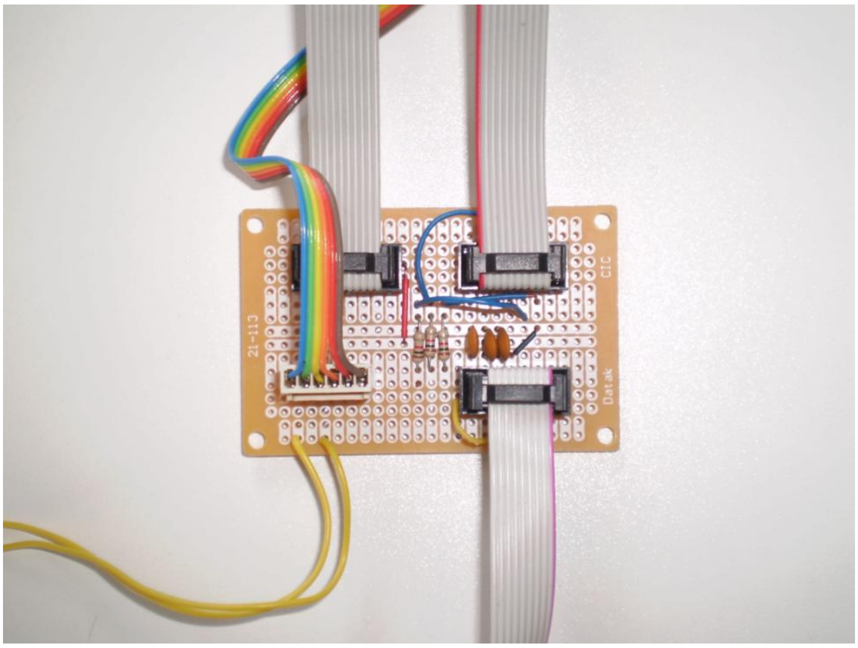

FIGURE 4-19: INTERFACE CIRCUIT BOARD.

The interface circuit board also includes a push button to reset the microcontroller, and is connected by the yellow wires shown in Figure 4-19. Ribbon cable is used to connect the two headers of the development board to the interface board. Data is transferred to the computer via a USB cable from the development board. This USB connection also provides all of the power required by the device, essentially making it a plug and play system.

4.4 Conclusion

The external Cardan joint device was designed in 3D modelling software and manufactured out of aluminium to minimise weight. The assembled prototype is mounted on a base platform, as shown in Figure 4-20, to accommodate a support for the forearm. Friction is reduced by ball bearings on each pivot and drive shafts allow a force feedback system to be implemented at a later date. A stress analysis of the likely forces applied by such a system found that the radial and axial loads on the bearings are well below their rated capacities.

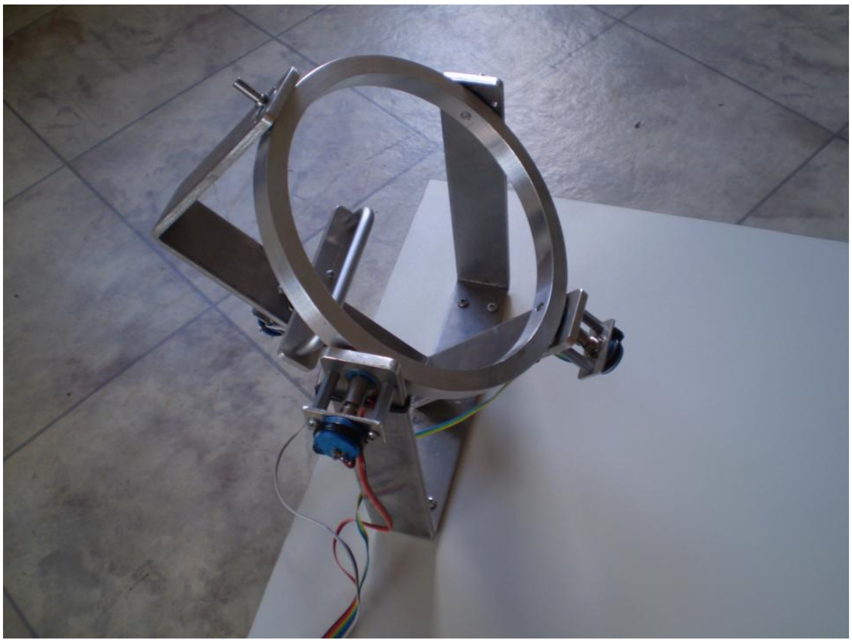

Figure 4-20: Device fully assembled and mounted on the platform.

Potentiometers mounted on each axis of rotation provide analogue voltages which directly relate to the position of the device. The signals from the potentiometers are processed through a low pass filter to eliminate unwanted interference. An Olimex PIC-MT-USB development board with an embedded 16F877A microcontroller is used to perform analogue to digital conversions on the potentiometer voltages and communicate with a computer via its USB port.

Chapter 5 SOFTWARE DESIGN

5.1 INTRODUCTION

This chapter outlines the two separate software design and developments in this research project. The microcontroller software is concerned with reading the analogue sensors, manipulating the raw data, displaying it to the user and sending it to the computer. Software on the computer is responsible for calculating wrist position and displaying this graphically on the screen in the context of a simple exercise game. Individual operation of the software programs and how they interact with one another will be discussed.

5.2 MICROCONTROLLER SOFTWARE

Code for the PIC16F877A was written in PICBASIC and developed in the *Oshonsoft PIC Simulator Integrated Development Environment* (IDE). This IDE enables the software to be simulated on the computer before being loaded onto the target microcontroller. The PICBASIC programming language is simple to use and contains an extensive library of relevant mathematical and functional commands. The microcontroller essentially performs three broad functions – data acquisition, user interfacing and communication with the computer.

5.2.1 FUNCTIONAL SPECIFICATION

The purpose of this specification is to provide an overview of the software and identify the functional tasks that the code must satisfy. The microcontroller software must fulfil the following objectives:

- Perform analogue to digital conversions on the potentiometer output voltages every 20ms.
- Convert this raw data to angular position in each axis.
- Display the data in raw or converted form on an LCD screen.
- Output the data serially to the RS232→USB chip on the development board.
- Allow the user to press buttons to change menus and calibrate the device.
- Store the calibration data and last menu state in EEPROM and recall this on power up.

5.2.2 Flow Chart

The flow chart in Figure 5-1 is a graphical representation of the microcontroller software program.

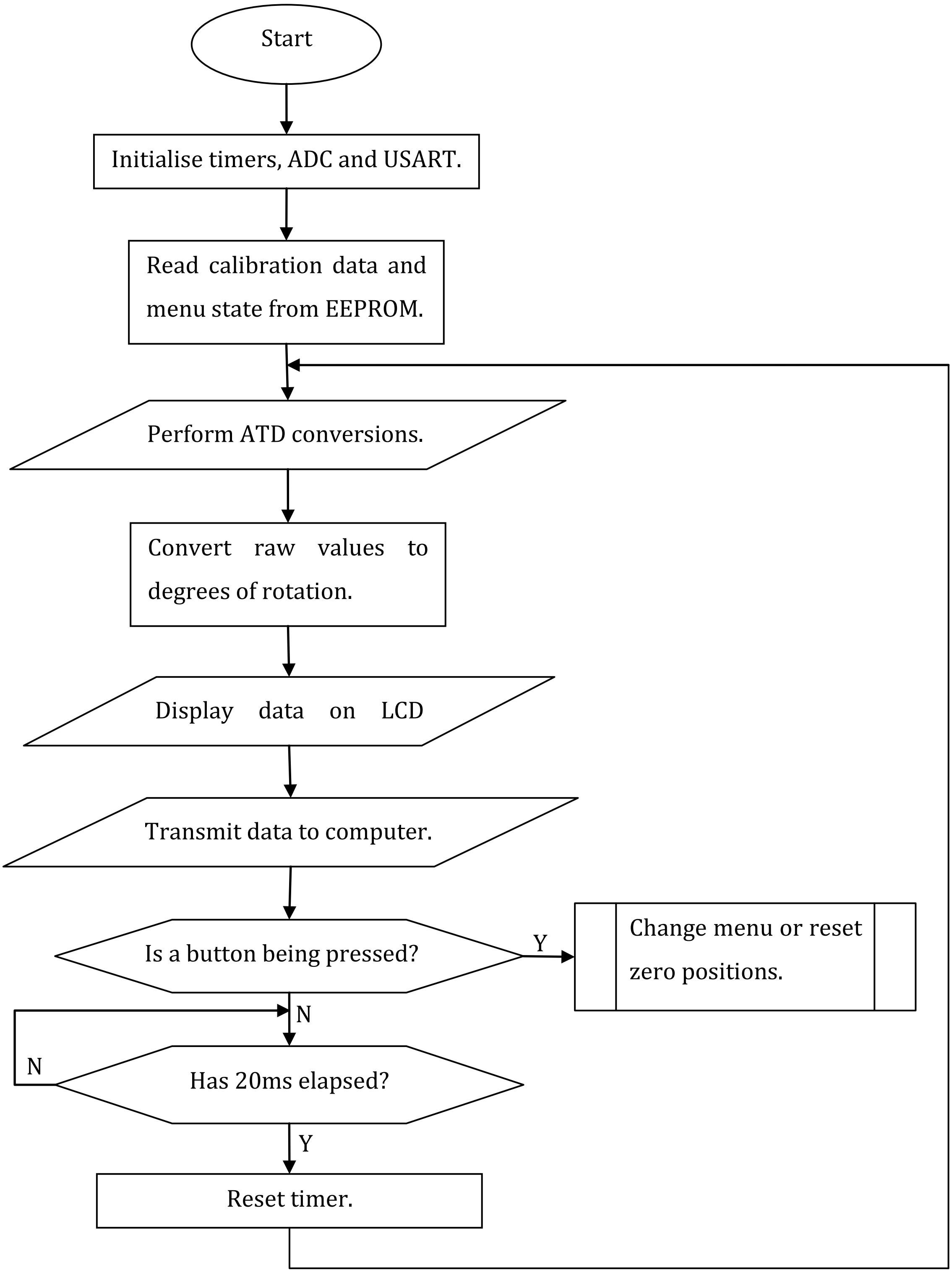

Figure 5-1: Microcontroller program flow chart.

5.2.3 Analogue to Digital Conversion

The ADC module converts each of the potentiometer voltages to digital numbers at the start of the main program loop. A timer is programmed such that the loop repeats every 20ms, so that the sampling rate is 50Hz. Three ADC channels are used, AN0, AN1 and AN3 which are selected in turn as each potentiometer is read. This choice of channels allows the other five ADC pins to be used for general purpose digital IO.

Resolution of conversion is initialised to be 10-bit and a conversion time of 20µs yields accurate results. Three numbers are stored from the ADC conversions, corresponding to each potentiometer voltage. These numbers range from 0 to 1023, proportional to the rotational positions of the potentiometer shafts.

5.2.4 User Interface

The user can manipulate the operation of the program with the two buttons on the development board. The alphanumeric LCD display provides useful information and gives an immediate visual indication of potentiometer position without necessarily running the computer software. On start up, a splash screen appears briefly on the display to indicate the purpose and designer of the software as shown in Figure 5-2.

Figure 5-2: Microcontroller splash screen.

The lower button is pressed to calibrate the potentiometers and this should be done every time a new patient uses the device. To calibrate, the patient should position their wrist in its neutral position and then press the lower button. The program will then record the raw ADC values obtained so that rotation of the wrist can be calculated relative to the neutral position. Hence, the calibration button effectively 'zeros' the display and stores the new calibration values in EEPROM. On start up, these calibration values are restored so that the device remembers the neutral position of the patient's wrist.

There are three different display modes, called raw mode, relative mode and rotation mode. When first powered up, the screen reverts to the last display mode that was previously active, which is retrieved from the EEPROM. To scroll through the modes of display, the upper button is pressed and released as many times as required. Raw mode, as shown in Figure 5-3, simply displays the 10-bit numbers obtained from the ADCs and is only included for debugging purposes and initial alignment of the potentiometer bodies. The M and S characters on the right of the screen indicate that the purpose of the buttons, Mode and Set.

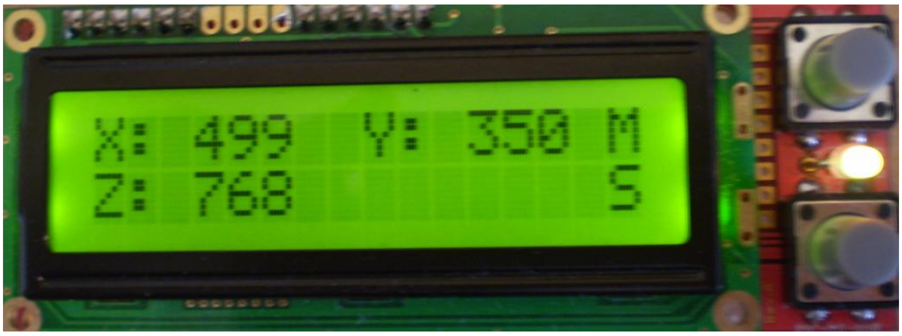

FIGURE 5-3: MICROCONTROLLER ADC RESULTS DISPLAY.

Relative mode displays the raw ADC results relative to the stored calibration values and therefore these can be positive or negative numbers. These relative numbers are also sent to the computer software by another subroutine. Letting RAW, CAL and REL represent the raw ADC value, calibration value and relative result respectively, the calculation of the relative ADC result for each potentiometer is shown in Equation 5.1:

$$REL = RAW - CAL \qquad (5.1)$$

In rotation mode, the relative values are converted to actual rotation of the potentiometers in degrees. The full mechanical rotational range of the potentiometers is 340°, hence each shaft angle θ can be found using Equation 5.2:

$$\theta = \frac{REL}{1023} \times 340° \qquad (5.2)$$

These rotation values are calculated and displayed on the development board LCD for the benefit of the user only and are not transmitted to the computer software.

5.2.5 DATA TRANSMISSION

The relative positions of the potentiometers are transmitted in a data sentence through the USART module of the PIC16F877A microcontroller. The RS232 to USB chip on the development board converts this transmission to the Universal Serial Bus (USB) standard and the computer receives the data through its USB port.

The data sentence consists of the signed relative values of each rotation preceded by a letter which identifies the specific potentiometer. For example, if the relative reading about the vertical axis (x) is 265, the horizontal axis (y) is -476 and the handle axis (z) is 987 then the resulting data sentence would be *x265y-476z987*. The sentence is transmitted serially in standard ASCII format and is terminated with a line feed (LF) character.

The maximum number of characters in the sentence is 19, which includes three identifying letters, three signed 4 digit numbers and a line feed. Each ASCII character is transmitted with a start bit, 8 data bits and a stop bit, totalling 10 bits each. The number of bits transferred per second is referred to as the baud rate of the transmission. Data transmission occurs every 20ms, as part of the main program loop operating at 50Hz. Hence, the minimum required baud rate for the transmission of the data sentence in a reasonable time of 10ms is calculated in Equation 5.3:

$$Min.Baud\ Rate = \frac{19\text{ chars} \times 10\text{ bits}}{0.01\text{ ms}} = 19000\text{ bps} = 19\text{ kbps} \qquad (5.3)$$

A standard baud rate of 56kbps is used for the transmission which is substantially faster than what is required. Communication with the computer is unidirectional, as data is only sent from the microcontroller to the PC. Data is continually streamed with no polling or acknowledgment required from the PC. Whilst this method is very fast, the responsibility lies with the computer software to ensure that the data can be retrieved from the serial buffer quickly enough that lag does not occur.

5.3 COMPUTER SOFTWARE

The computer program presented in this section is an integral component of the wrist rehabilitation system and has been designed specifically for use with the prototype device. Software was developed in *Visual Basic 2008 Express Edition* which is freely available online from Microsoft. The Visual Basic language was chosen for its simplicity and ability to create visually appealing, Windows form based applications.

This computer program aims to provide the patient with visual stimulus and structured exercise games to increase motivation for movement therapy rehabilitation. The therapist will expect the software to record movement and objectively assess patient condition to assist them with evaluation. This section will outline the requirements of the rehabilitation software and discuss how they are fulfilled in its operation.

5.3.1 FUNCTIONAL SPECIFICATION

The computer software should aim to fulfil the following functions:

- Log patient movement.
- Objectively assess and record patient condition.
- Display movement of the wrist on the screen.
- Provide visual stimulus in the form of computer games to exercise the wrist through an appropriate range of motion.
- Allow the therapist to specify maximum limits of wrist motion.
- Include playback tools for evaluation by a therapist.

5.3.2 DATA FLOW

The software for the computer has been developed as two separate forms. The RS232COM form is responsible for retrieving data from the serial port when a data sentence arrives from the microcontroller. On receipt of a valid data sentence, the RS232COM form sends this data to a separate form called MainApplication. This form is responsible for the graphical user interface, data processing and video game. A full listing of software code of both of these forms is in Appendix C.2.

5.3.3 VISUAL DISPLAY

A visual display must be able to intuitively and accurately display the position of the wrist onto a computer screen. The three rotational degrees of freedom are to be conveyed logically a two-dimensional workspace in a manner which is easily understood by a stroke patient with likely cognitive deficits. The endpoint of the device is represented on screen as a crosshair cursor within a two-dimensional environment as shown in Figure 5-4.

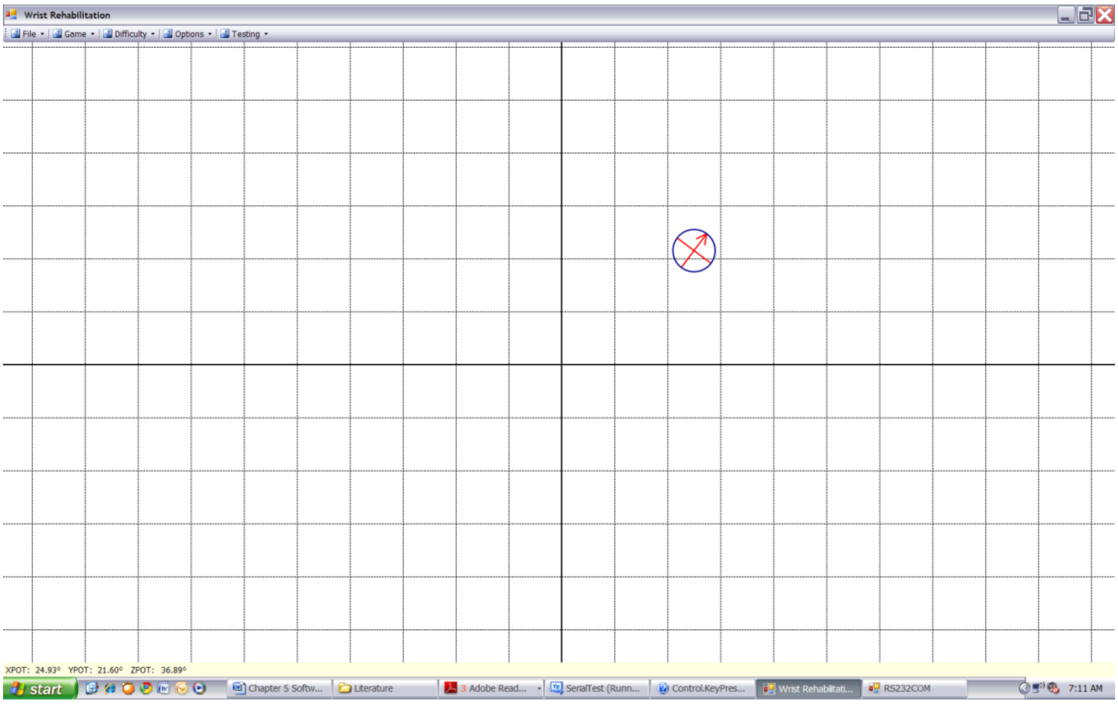

FIGURE 5-4: VIRTUAL REPRESENTATION OF WRIST POSITION ON THE SCREEN.

The x-coordinate of the target position corresponds to flexion/extension of the wrist and the y-coordinate corresponds to abduction/adduction. Rotation of the forearm is indicated by the direction of the arrow inside the cursor crosshairs. The device should be calibrated such that the end effector handle is vertical when the arrow is pointing directly upwards. This choice of orientation better displays the motion of the end effector on a wide screen, recalling that the wrist's range of movement in flexion/extension is significantly larger than that in abduction/adduction.

Another mode of display can be selected which neglects the actual wrist position and simply plots the cursor at the point corresponding to the rotation of the potentiometer axes. Therefore, this mode only represents true wrist position when the handle is exactly upright and no forearm rotation is present.

An optional grid can be displayed with each space between adjacent lines representing 10° of rotation. The thick black lines intersecting at the centre of the screen indicate the neutral positions of flexion/extension and adduction/abduction. Figure 5-5 shows the target displayed at the neutral position of the wrist with no rotation of the forearm for a properly calibrated device.

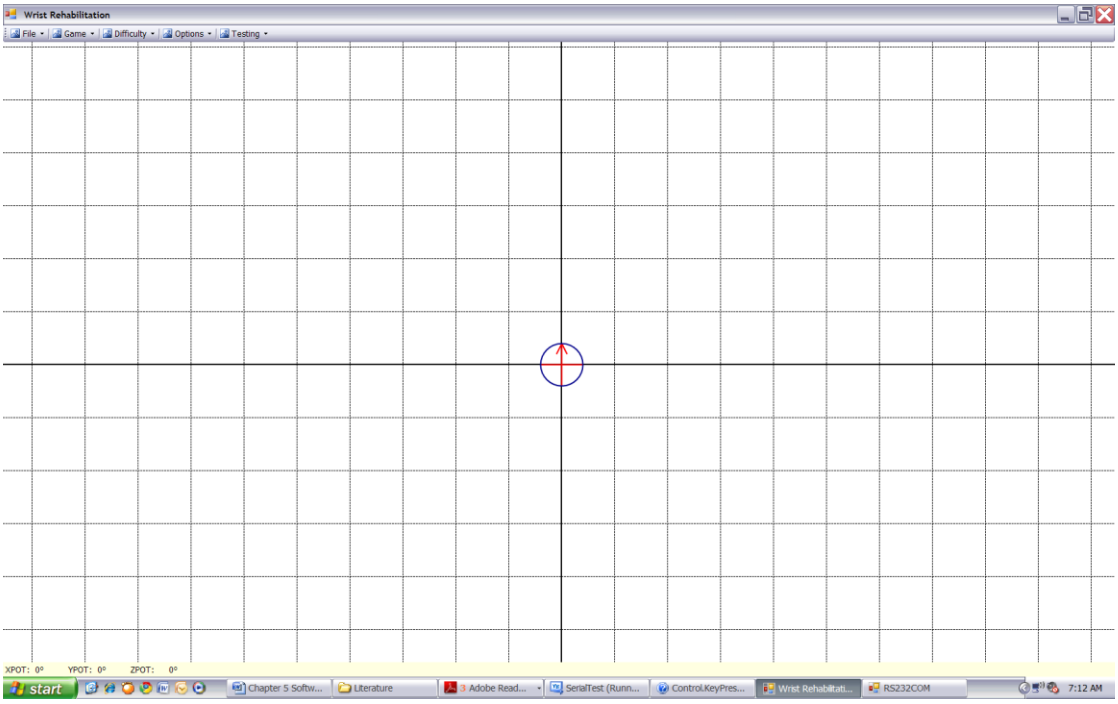

FIGURE 5-5: GRAPHICAL REPRESENTATION OF THE WRIST IN ITS NEUTRAL POSITION

Calculation of the degree of wrist motion is rather straightforward when the device handle is in the neutral upright position. In this case, the angles measured on the vertical and horizontal axes of the device correspond to flexion/extension and abduction/adduction of the wrist respectively. Any rotation of the forearm, however, removes this direct relationship and trigonometric equations are required. Let θ_x, θ_y and θ_z represent rotation about the vertical, horizontal and handle axes respectively as depicted in Figure 5-6.

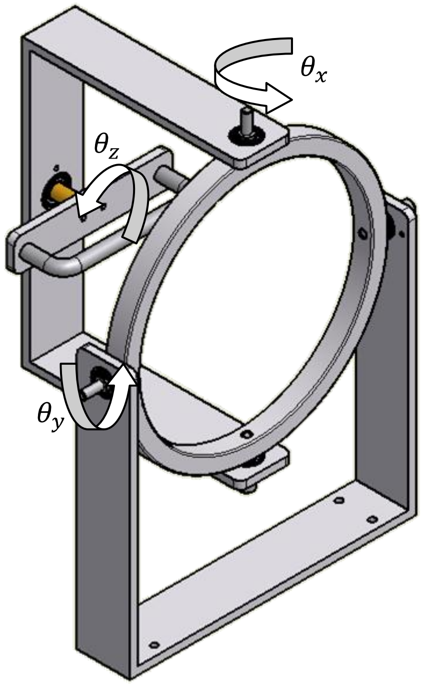

FIGURE 5-6: AXES OF ROTATION OF THE DEVICE.

Extension and abduction of the right hand wrist can be calculated from Equations 5.4 and 5.5:

$$\theta_{ext} = \theta_x \cos\theta_z - \theta_y \sin\theta_z \qquad (5.4)$$

$$\theta_{abd} = \theta_y \cos\theta_z + \theta_x \sin\theta_z \qquad (5.5)$$

Note that negative extension represents flexion and likewise, adduction is simply negative abduction. Rotation of the forearm is always measured directly from θ_z axis which is positive in the pronation direction for the right hand and in the supination direction for the left hand. Handedness of the patient must also be taken into account in the calculation of extension and abduction, as the motion of the left hand is the mirror image of the right hand. Hence, for a left hand wrist, Equations 5.6 and 5.7 are appropriate:

$$\theta_{ext} = -\theta_x \cos\theta_z + \theta_y \sin\theta_z \qquad (5.6)$$

$$\theta_{abd} = \theta_y \cos\theta_z + \theta_x \sin\theta_z \qquad (5.7)$$

These calculated values of wrist motion are displayed in the status bar at the bottom of the screen as shown in Figure 5-7.

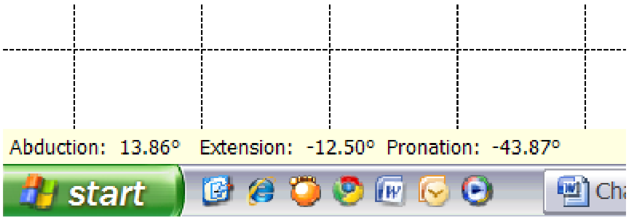

FIGURE 5-7: DISPLAY OF WRIST POSITION IN THE STATUS BAR.

5.3.4 *VIDEO GAME*

A simple computer game generates random targets within a maximum range of motion specified by the therapist. Figure 5-8 shows the cursor moving towards the green target which changes position when the centre of the crosshair enters the circle. When reached, the target returns to centre of the screen, forcing the patient to move their wrist to its neutral position before a new random target is generated.

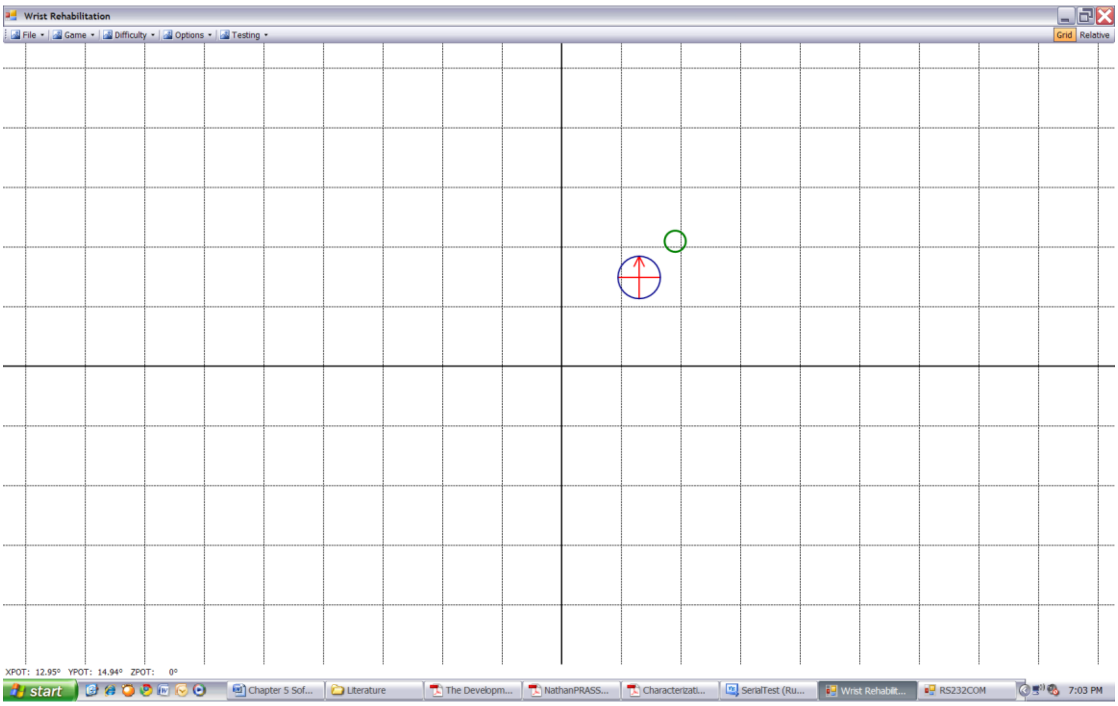

FIGURE 5-8: CURSOR CROSSHAIRS MOVING TOWARDS A GAME GENERATED TARGET.

The game is toggled on and off through the drop down box in the menu bar as shown in Figure 5-9. Size of the target circles can be varied to change the difficulty of the game depending on patient condition. The difficulty is selected from the menu bar as shown in Figure 5-10.

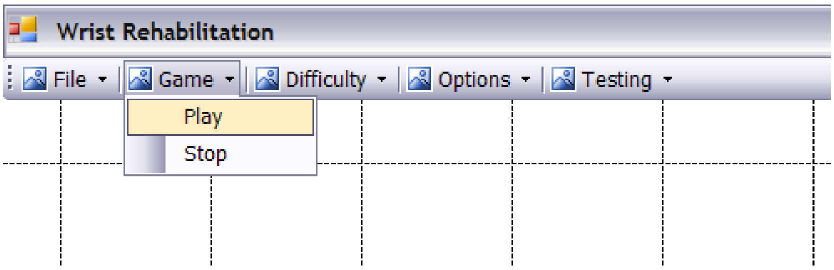

FIGURE 5-9: GAME MENU.

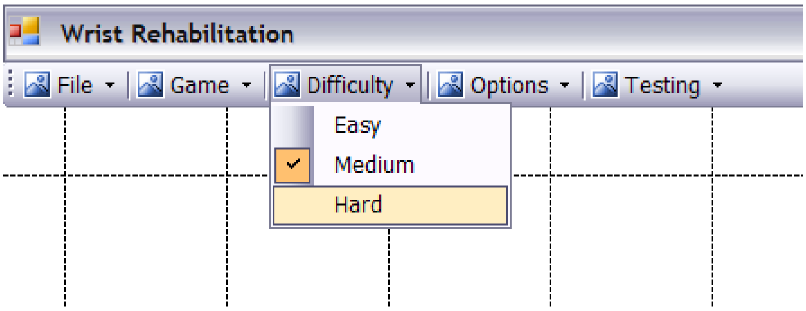

FIGURE 5-10: SELECTION OF TARGET DIFFICULTY.

The therapist is able to specify the maximum ranges of motion targeted by the video game in the options menu as shown in Figure 5-11. Appropriate limits of motion are simply entered into the corresponding menu textbox. This options menu also contains buttons to toggle the display grid and select the handedness of the patient.

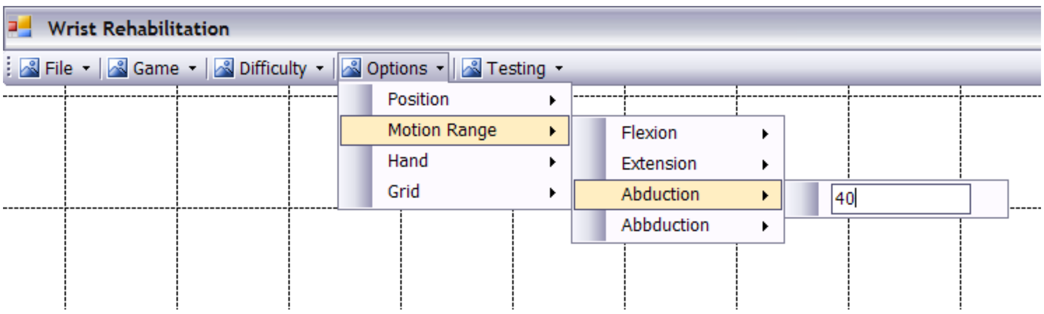

FIGURE 5-11: CHANGING THE MAXIMUM ALLOWABLE RANGE OF MOTION.

5.3.5 *Limitations*

At this stage in the software development, the rotation of the wrist is not actively engaged in the video game. It is anticipated that exercise games involving supination/pronation of the wrist will be developed as the project is continued. An example game may require the patient to rotate an onscreen shape with their forearm to match an appropriate outline in the virtual world.

Logging of movement data is also a feature which is yet to be implemented. When the patient is using the video game, movement data should be logged so that the physical therapist can assess the patient's condition. It is anticipated that further development of the software will also include tools to automatically assess patient condition from this logged data.

The development of this software was not intended to be the major accomplishment of this project. Rather, its purpose is to demonstrate how movement captured on the designed wrist device can be translated to a virtual environment in an entertaining and intuitive manner.

5.4 Conclusion

Software for the microcontroller and computer have been developed and successfully integrated to create a visual display of the wrist position. The microcontroller software effectively reads the analogue signals from the potentiometers, displays the device position to the user and transfers data to a computer via USB. Computer software manipulates this position data, calculates actual extent of wrist motions and displays a representation of these on the screen.

A simple video game has been developed to exercise the wrist movements of flexion/extension and abduction/adduction over an appropriate range of motion. This game aims to emulate movement therapy traditionally administered by a physical therapist. It was not developed as a high-end, visually stunning video game but rather to demonstrate the device's potential for automated movement therapy. It is hoped that the design of further video games will be undertaken in the future to include rotation of the forearm and improve the method in which movement is presented on screen.

Chapter 6 TESTING & ANALYSIS

6.1 INTRODUCTION

Testing of the hardware and software was undertaken to quantify the device's value as a rehabilitation aid. This chapter will revisit the specific device requirements, outline the evaluation procedures and analyse the results obtained from testing the performance of the device. Discussion of the findings will follow, including a critical comparison between the expected and actual performances of the device and any limitations identified.

6.2 RANGE OF MOTION

An important requirement of this device is to accommodate a large range of unimpeded wrist motion as discussed in Chapter 3. To begin with, the physical extents of the device with the handle fixed in the vertical position were plotted as a black line on screen using a range of motion test routine in the computer software, as shown in Figure 6-1. Recall that flexion/extension is measured on the horizontal axis and abduction/adduction on the vertical axis. The distance between the gridlines represents 10° of rotational motion.

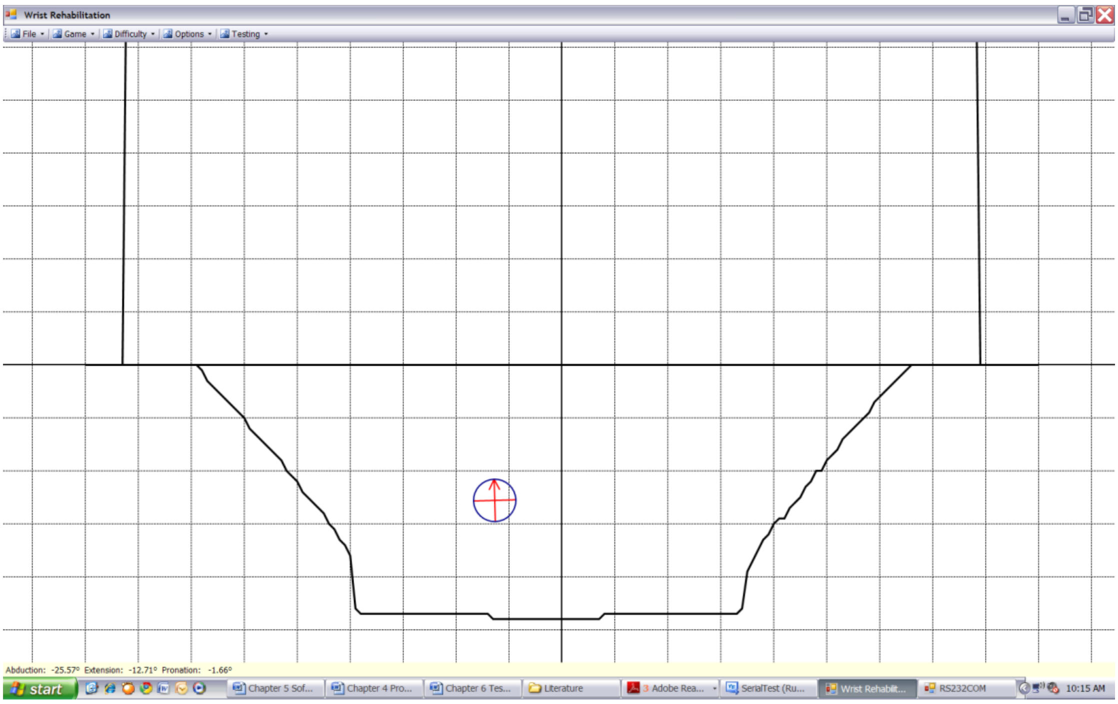

FIGURE 6-1: PHYSICAL EXTENTS OF DEVICE MOVEMENT WITH HANDLE FIXED VERTICALLY.

The flexion and extension limits in the region of positive abduction (above the x-axis) are approximately ±80° which is due to the pivoting fork clashing with the uprights of the fixed fork as photographed in Figure 6-2. As the end effector moves into adduction, the range of flexion/extension is seen to decrease as the mechanical structure of the device limits the movement. The range of abduction is virtually unlimited as there is nothing stopping the device from being rotated 180° about the horizontal axis. Adduction is limited to about 48° due to the inability of the pivoting fork to rotate in the negative direction about the horizontal axis past the base fork as depicted in Figure 6-3.

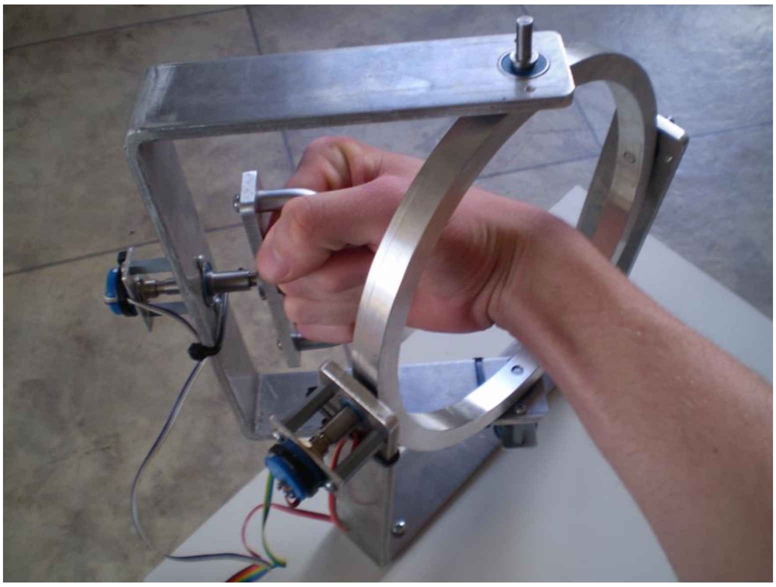

FIGURE 6-2: MECHANICAL LIMIT OF FLEXION/EXTENSION MOTION DUE TO COMPONENT INTERFERENCE.

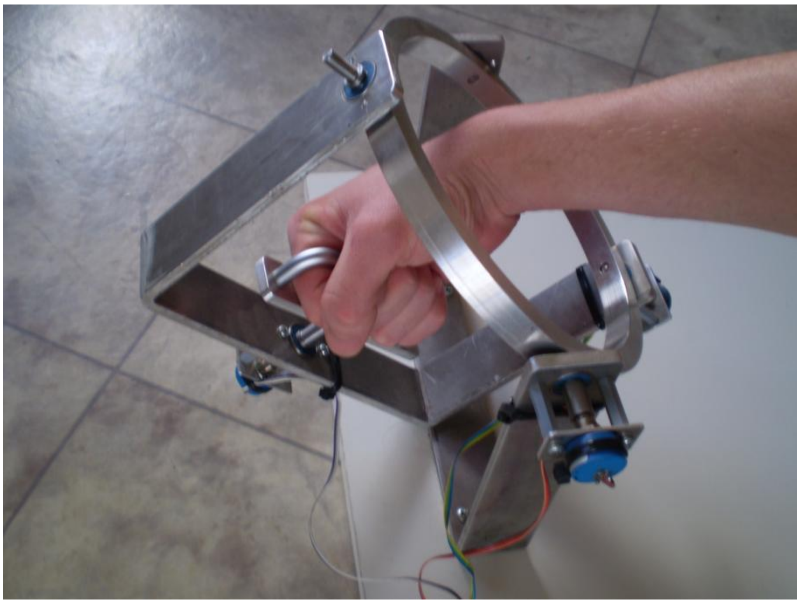

FIGURE 6-3: MECHANICAL LIMIT OF ADDUCTION MOTION DUE TO COMPONENT INTERFERENCE.

Recall the maximum range of motion of the wrist and the minimum ROM required to perform activities of daily living specified in Chapter 3. The achieved range of motion is presented for comparison with these desired and minimum ROMs in Table 6-1.

TABLE 6-1: DESIRED, MINIMUM AND ACHIEVED RANGES OF MOTION.

Movement	Range of Motion		
	Desired	**Minimum (ADL)**	**Achieved**
Wrist Adduction	30°	40° combined radio-ulnar deviation.	48°
Wrist Abduction	15°		Unlimited
Wrist Flexion	85°	40°	80°
Wrist Extension	85°	40°	80°
Forearm Pronation	85°	70°	Unlimited
Forearm Supination	90°	70°	Unlimited

The range of motion of the device comfortably exceeds the minimum ROM required to perform activities of daily living and accommodates the entire range of wrist and forearm motion with the exception of flexion/extension, which is only slightly below the desired ROM. One must also consider, however, that the forearm can be rotated to orient the wrist such that flexion or extension can occur on the unlimited direction of rotation about the horizontal axis.

Nevertheless, for the device to accommodate all maximum ranges of motion at any rotational position of the forearm would require redesign of the mechanical structure. For instance, the additional degree of flexion/extension movement could be obtained by widening the base fork. Similarly, increasing the horizontal pivot height would prevent the forks clashing at the extent of adduction. Both of these modifications represent a trade-off between device size (and inevitably weight) and range of movement. The design of the prototype as it stands has proven to be sensible compromise given its exceptional range of movement.

The device was also tested with the wrist grasping the handle and the forearm constrained. The maximum range of movement of the author's wrist was measured and displayed in Figure 6-4. One can clearly see a rough ellipse representing the cone of circumduction of the wrist. This ellipse is seen to lie within the mechanically limited workspace shown in Figure 6-1, indicating that movement of the wrist is well accommodated by the design. The apparent unnaturally high degree of radio-ulnar deviation shown is most likely due to poor restraint of the forearm during testing.

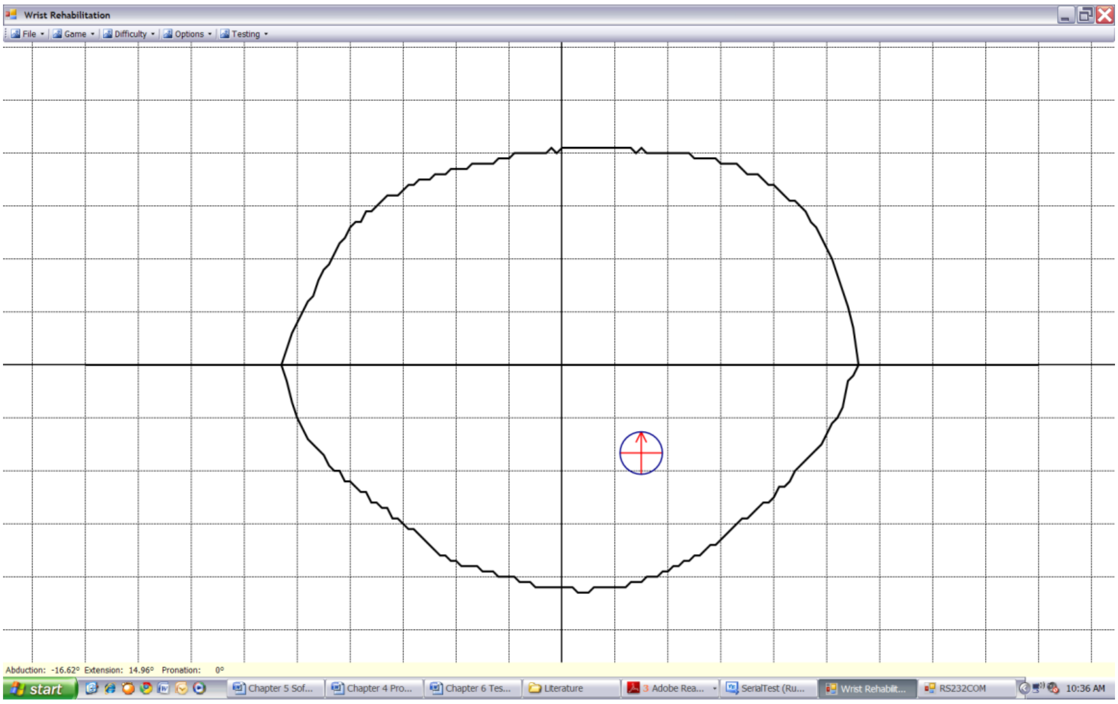

FIGURE 6-4: RANGE OF MOVEMENT OF THE AUTHOR'S WRIST IN THE DEVICE.

Testing of the range of motion has found that the device exceeds the design requirements and successfully accommodates the large and complex ROM of the human wrist. Although insignificant, the limitation of flexion/extension could be negated by redesigning the device with a wider base fork. Heightening of the base fork would also remove the mechanical limitation of movement in adduction. However, modification of the mechanical structure is deemed unnecessary considering the limited improvement of ROM and significant increase in device size that would inevitably result.

6.3 Position Capture

The representation of the wrist position on screen should accurately reflect the position of the wrist in the real world. To quantify how well the device captures position, the accuracy and precision of the on screen representation will be analysed. The position of the device was manipulated to exact known angles using a protractor as shown attached to the output shaft of the vertical pivot in Figure 6-5.

FIGURE 6-5: PROTRACTOR MOUNTED ON THE DEVICE FOR POSITION TESTING.

Only one degree of freedom was tested, as it is assumed that the accuracy of all position sensors will be reasonably similar. The pivot fork of the device was rotated on the vertical axis through a number of positions, equally spaced at 10° from the neutral position shown in Figure 6-6. The values of on screen rotation were recorded as displayed in the status bar of the computer application.

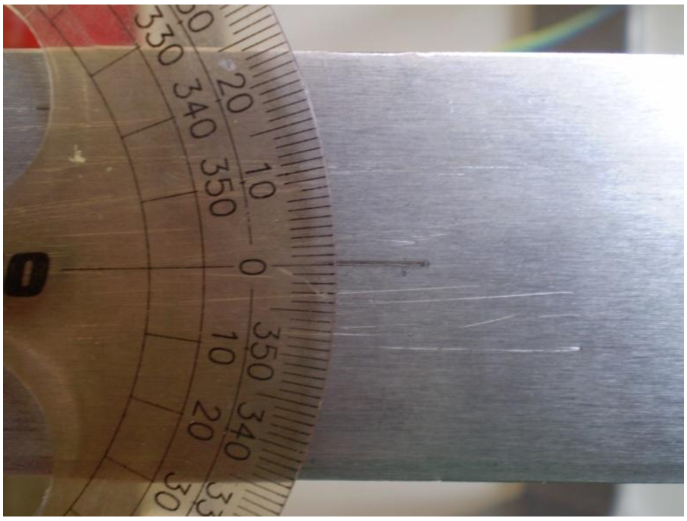

FIGURE 6-6: PROTRACTOR SHOWING THE PIVOT IN THE NEUTRAL POSITION.

Table 6-2: Testing of on screen position representation.shows the actual rotation of the device against the rotation displayed on the computer screen for four independent samples. The angles of the non-tested axes of rotation were changed for each different sample, in order to quantify whether the positions of those axis affected the accuracy of the axis being tested.

TABLE 6-2: TESTING OF ON SCREEN POSITION REPRESENTATION.

Actual Rotation	On Screen Rotation			
	Sample 1	Sample 2	Sample 3	Sample 4
60°	60.8°	60.5°	60.2°	60.2°
50°	50.5°	49.9°	50.2°	49.9°
40°	40.6°	39.9°	39.6°	40.2°
30°	29.9°	29.9°	29.9°	30.2°
20°	19.6°	19.2°	19.6°	19.6°
10°	9.6°	9.3°	9.3°	9.3°
0°	0°	-0.3°	0.3°	0°
-10°	-10.9°	-10.9°	-10.9°	-10.9°
-20°	-21.6°	-21.2°	-21.2°	-20.9°
-30°	-32.2°	-31.9°	-31.6°	-31.6°
-40°	-41.8°	-42.2°	-41.8°	-41.8°
-50°	-51.8°	-52.2°	-51.8°	-51.8°
-60°	-62.5°	-62.5°	-61.8°	-62.2°

This errors from the data presented in Table 6-2: Testing of on screen position representation.Table 6-2 were calculated and displayed in the form of a whisker plot as shown in Figure 6-7. The chart plots a whisker between maximum and minimum error, with the red triangle indicating the average error. Accuracy is represented by the distance of the average error from the horizontal axis whereas precision is determined from the length of the whisker.

The accuracy of the device is acceptable in the region of positive rotation, with errors falling within ±1°. Interestingly, errors of up to -2.2° occur consistently in the negative direction of rotation, suggesting that there may be an error in the calculation of rotation. A more likely explanation is a slight non-linearity of the potentiometer output. A substantial amount of error was also inevitably introduced by the visual alignment of the fork to the protractor.

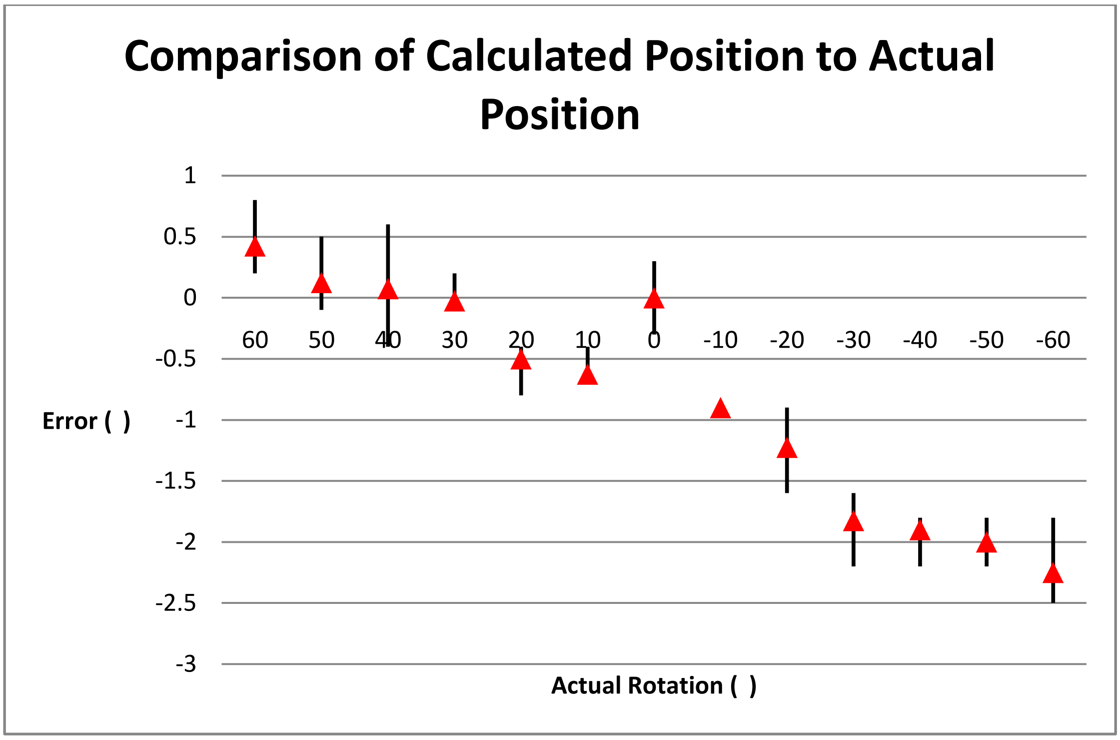

FIGURE 6-7: ERRORS IN THE REPRESENTATION OF ROTATION ON THE SCREEN.

Precision of the results is outstanding, as demonstrated by the relatively small difference between maximum and minimum errors. The requirement of ±1° precision stated in Chapter 3 appears to be fulfilled by the system which consistently demonstrates a precision of ±0.5°. This suggests that there is minimal cross talk interference between potentiometer voltages, as the results remained steady despite the varying output voltages from the other potentiometers.

Hence, testing of position capture has shown that the device represents position on the screen with high precision and reasonable accuracy.

6.4 Device Useability

The useability of the device depends on a number of characteristics, including movement impedance, smoothness of position capture and comfort of operation. Because measurements of these properties are difficult to quantify, the conclusions presented in this section are speculative only.

When the forearm is properly supported, the effort that must be exerted by the wrist to support the device against gravity is significant but not overwhelming. Because the device has been developed with the intention of implementing force feedback at a later stage, no attempt to counteract the torque caused by gravity has been made. As a result, the device is not truly passive and extended use does tire even a healthy wrist. Use by a stroke patient with a significantly weakened wrist is probably unreasonable until the force generation system is developed.

Resistance of movement due to the inertia of the cross ring and pivot fork is negligible, particularly at the small magnitudes of acceleration required. The bearings at the pivots are successful in minimising friction, although there is some noticeable binding due to their interference fit in the forks. Modification of the design to include proper bearing housings is recommended to overcome this problem.

Smoothness of position capture on screen is excellent, with no noticeable lag in the display of motion. The refresh rate of 50 Hz results in very smooth onscreen movement and resolution of the position display is excellent. Some jitter of the position crosshair on the screen is apparent, and this has been found to be caused by electrical interference in the ribbon cable connecting the device to the development board. Replacing this cable with a shielded computer cable should eliminate this jitter.

Comfort of operation is not exceptional, although its importance in the development of an initial prototype is questionable. It is anticipated that redesign of the prototype for use in a clinical trial would include a compliant handle with strapping to secure the hand. A forearm restraint would also take significant stress off the lower arm in attempting to hold the forearm still.

6.5 System Limitations

As expected for a prototype development, a number of limitations and problems have been identified. Whilst most of these are specific to either the software or hardware designs, their impact on the overall system is inevitable. Limitations which have been identified include:

- The press fit of bearings into the forks has caused slight deformation of the bearing outer, resulting in some noticeable binding. Design of housings to prevent axial movement of the bearing and eliminate the need for the press fit into the fork holes is recommended.
- Accuracy of onscreen position representation is limited to ±2° in some regions of potentiometer shaft rotation which is significantly lower than the expected accuracy of ±1°. The modification of position calculations to include non-linearity of the potentiometer outputs could resolve this limitation.
- Some minor jitter of the onscreen cursor is apparent and is most likely caused by high frequency interference picked up on the ribbon cable connecting the interface board to the potentiometers. The use of shielded computer cable is recommended to eliminate any such interference.

6.6 Conclusion

Testing of the wrist rehabilitation device prototype and associated software has been exceedingly positive. The device is able to accommodate the entire range of movement and complex combinations of wrist motion. The precision of the position capture was found to exceptional, although accuracy of the device was slightly lower than anticipated. Useability of the device was assessed according to its movement impedance, smoothness of movement capture and comfort of operation.

The device has proven to effectively capture movement of the wrist and display this onscreen with high precision and acceptable accuracy. However, the identification of limitations shows that slight modification of the mechanical design and development of a force generation system are essential if the device is to be used for stroke rehabilitation.

Chapter 7 CONCLUSIONS

7.1 INTRODUCTION

The work undertaken in this research project represents a significant step towards the development of a force-feedback wrist rehabilitation device for movement therapy. This has involved the detailed design and construction of a prototype device and electronic hardware to capture movement of the wrist and rotation of the forearm. Computer software has also been developed to represent the wrist position on a computer screen and administer movement therapy in the context of a simple video game.

This chapter will summarise the work documented in this dissertation and discuss how the initial goals have been accomplished. A review of the system's limitations and suggestions for future work will follow.

7.2 GOALS ACCOMPLISHED

The overall goal of this project was to design and develop a wrist rehabilitation system for movement therapy. The realisation of this goal from the concept development through to the detailed design of the mechanical hardware and software can be summarised by the following accomplishments:

- Background research was undertaken to gain a broad understanding of stroke therapy and factors relevant to the development of a rehabilitation device. The biomechanics of the wrist were examined as well as the causes and outcomes of stroke. Rehabilitation was discussed in the context of its mechanisms, current therapy techniques and outcomes. Automated therapy was compared with traditional methods in terms of their inherent advantages and limitations. The background research and literature review in Chapter 2 were essential in directing the design of the wrist rehabilitation system.
- A number of concept designs were developed and analysed against a set of established requirements in Chapter 3. These requirements included specification for movement impedance, range of motion and accessibility of the device. The merits of the concept designs were critically compared and the chosen design took the form of an external Cardan joint which encompasses the wrist. Possible methods of position sensing and data capture were also discussed and evaluated.

- Detailed design of the prototype system's mechanical and electronic hardware was undertaken as described in Chapter 4. This included the justification of design decisions and selection of system components. The prototype device was manufactured from detailed drawings and assembled as pictured in Figure 7-1. The development of the prototype mechanical hardware represented a significant milestone in this research project. Electronic hardware was designed to interface the device to computer software by reading the sensors, manipulating & transferring the data and displaying position information to the user.

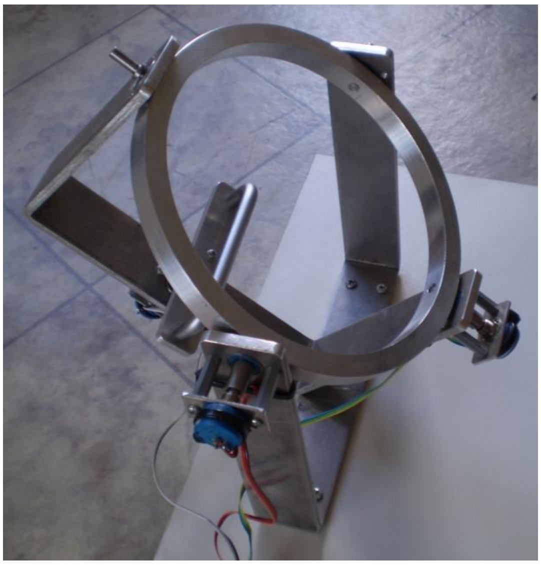

FIGURE 7-1: PHOTOGRAPH OF THE ASSEMBLED PROTOTYPE.

- Chapter 5 highlights how the development of software for the computer and the microcontroller transforms the prototype device into an interactive system which has great potential as a rehabilitative aid. A computer program was developed to process the data retrieved from the mechanical device and succeeded in displaying the position of the wrist and forearm as a visual representation on the screen. The primitive video game developed demonstrates the potential of the software to administer automated movement therapy.

- Testing of the overall system was conducted in Chapter 6 and specific analysis of hardware and software designs was undertaken. Analysis of the results found that the device satisfies and often exceeds the functional requirements stated in Chapter 2. A few design problems were identified and suggestions to overcome these were given. The overall findings of the testing and analysis phase suggested that the therapy system developed is highly capable of measuring a broad range of complex wrist & forearm motion and representing this on a computer screen in an intuitive and entertaining manner.
- The remainder of this chapter will suggest future work to be done on the project, including the implementation of a force-feedback system.

7.3 Future Work

The identification of the system's limitations in Chapter 6, incomplete work due to time constraints and broad scope of this project leave considerable opportunity for future development of the device hardware and software. Suggestions of future system development will be discussed separately in terms of hardware and software improvements.

7.3.1 Hardware

The major scope for future work involves the development of a force generation system to be implemented on the device. This generation of force may be as simple as passively counteracting the force of gravity or as complex as actively assisting and resisting patient movement. Counteracting the force of gravity would significantly increase the device's rehabilitative potential by decreasing the strength required to support the wrist in the device.

An example of a passive approach to force generation is shown in Figure 7-2. This shows the attachment of a counterweight to the drive shaft on the horizontal axis. The counterweight effectively cancels the torque generated by the mass of the pivoting fork and end effector. The torque will only be in balance at one point in the rotation of the pivot fork about the vertical axis as changing this position varies the distance of the end effector mass from the horizontal pivot. Nevertheless, the counteracting torque provided by the counterweight would go some way to reducing the force on the patient's wrist.

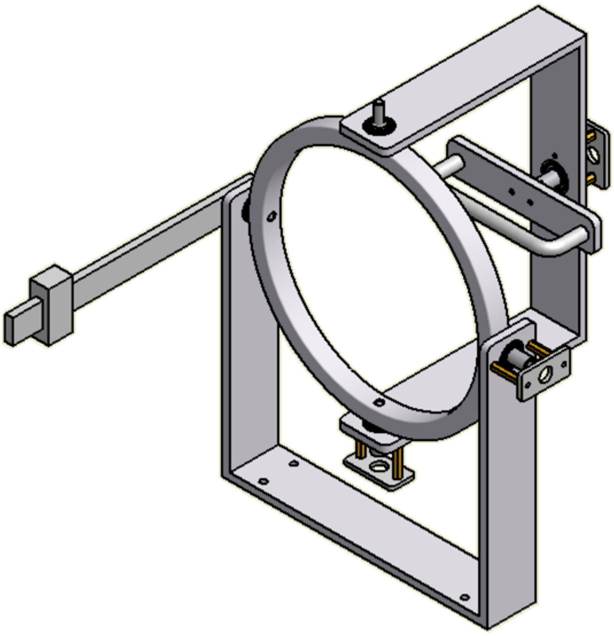

FIGURE 7-2: PASSIVE FORCE GENERATION USING A COUNTERWEIGHT.

To overcome the limitations of passive force generation, an active electromechanical force feedback system could be developed. Such a system might involve electric motors, actuators or solenoids to generate force. The example device in Figure 7-3 has an electric motor mounted to generate torque about the horizontal axis of rotation. It is anticipated that motors could be mounted on the device to drive each axis of rotation independently.

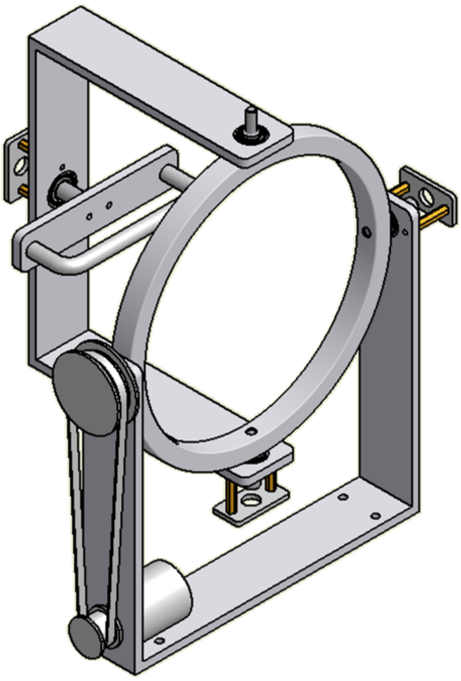

FIGURE 7-3: POSSIBLE ACTIVE FORCE FEEDBACK SYSTEM.

An active force feedback system would not only be able to vary the torque required to counteract gravity but also assist and resist patient movement. The ability to exert force on the wrist would allow the device to administer strengthening exercises in addition to passive movement therapy. The scope for development of a force feedback system is immense, and significant research would have to be undertaken to determine how to apply the force in a smooth, human like manner in order to emulate traditional physical therapy.

Before implementing a force feedback system, some modifications should be made to the mechanical structure of the device. Future work includes redesigning the bearing housings to avoid the press fit of the bearings in the forks and designing a restraint for the forearm. Furthermore, redesign of the device with a soft handle and aesthetically pleasing exterior would go some way to seeing the system succeed commercially as a rehabilitation aid. Research into the use of plastics and other lightweight materials in the manufacture of the mechanical structure could also dramatically reduce the weight of the device.

Replacement of the ribbon cable connecting the device to the interface board with shielded computer cable is also recommended to decrease interference which is manifesting itself as jitter on the screen. The electronic hardware could also be improved by the design of a printed circuit board for the interfacing circuit and the mounting of all hardware, including the development board, in a neat box.

The slightly lower than expected accuracy of the device should be investigated including an analysis of potentiometer linearity. It is anticipated that the implementation of a force feedback system would require greater accuracy from the sensors in order to obtain a desirable control loop. The use of more expensive or different kinds of sensors may be found to increase accuracy significantly. Future development of the device may also include an investigation into the use of machine vision in calculating position of the wrist.

Clearly, the development of a force feedback system is the major thrust in the further development of this device. The realisation of such a system will most likely involve little modification, due to the effort made to accommodate force feedback in the design of the passive device.

7.3.2 *Software*

The software developed in this research study was purely intended to demonstrate the potential of the device to communicate with a computer. As so, there is significant scope for development of rehabilitation software targeting the wrist motions captured by the device. The three major aims of the software are to display motion on the screen, log the movement and assess patient condition from the movement data.

The current software represents position of the wrist on the screen very well, however rotation of the forearm is understated. The enhancement of graphics is also required, in order to entertain the patient during their movement therapy. Video games which target not only the wrist, but also the forearm should be developed in future undertakings of this project. Such a game may use shapes which must be translated with the wrist movements and rotated with the forearm to align with matching targets on the screen.

The logging of movement data is also required so that valuable information can be passed to the therapist. Data logging should be a reasonable simple exercise for a computer engineer to implement in the software, as the retrieval of data has already being accomplished. A method of redisplaying previously captured data on the screen should also be investigated, as this would provide meaningful feedback to the patient after each therapy session.

Assessment of patient condition is perhaps the greatest challenge in the further development of the software. Significant research would have to be undertaken to determine the most effective means of objectively measuring patient ability. Current research suggests that existing performance measures are not well suited to stroke patient assessment, so the development of a computer calculated performance measure is by no means a light exercise.

The design of rehabilitation software which actively engages the patient, whilst giving a high level of control and feedback to the therapist is essential to the success of the rehabilitation system presented in this study.

7.4 Conclusion

This study has proven that a device for rehabilitation of the wrist can be developed at a low cost whilst fulfilling the essential requirements for such a therapy system. The device designed is successful in capturing natural human wrist movement over a large and complex range of motion. Testing has also validated that the form of the mechanical structure is well suited to the biomechanical behaviour of the wrist.

The design of software including an intuitive visual interface and simple computer games which emulate movement therapy, demonstrates the potential of computer aided rehabilitation. Representation of the patient's wrist position on the computer screen has been achieved with high precision and reasonable accuracy. The video game developed also encourages the patient to move their wrist through an appropriate range of motion, essentially emulating movement therapy traditionally administered by a physical therapist.

Future development of the rehabilitation system should include the implementation of force feedback to convert it from a passive to an active device. The advantage of such an active system lies in its ability to assist and resist patient movement, effectively strengthening muscles and improving cognitive awareness of the patient. Furthermore, the mechanical design of the device should be refined with the intention of testing the system by means of a clinical trial.

Research and design work undertaken in this project represents a significant step towards the realisation of a therapy system which is ready to be used in a clinical trial. It is hoped that technology such as that presented in this dissertation, is adopted by stroke patients as an alternative to intensive one-on-one rehabilitation with a physical therapist.

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APPENDIX A PROJECT SPECIFICATION

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **Blythe Jonathan GARRATT**

TOPIC: THE DEVELOPMENT OF A WRIST REHABILITATION DEVICE FOR MOVEMENT THERAPY.

SUPERVISOR: Dr. Selvan Pather
University of Southern Queensland

PROJECT AIM: To design, construct and test an electromechanical device to enhance the physical rehabilitation of stroke patients who have impaired motor function in their wrists. The device will interact with a computer interface and simple computer games to allow the physiotherapist to quantitatively monitor rehabilitation progress whilst maintaining patient interest.

PROGRAMME: (Issue B, 25th May 2009)

1. Research wrist physiology and the effects of stroke on human motor control.
2. Assess current rehabilitation practices, physical therapy and robot-assisted therapy.
3. Critically evaluate existing therapy devices targeted at wrist muscle rehabilitation.
4. Design and construct a novel therapy device targeted at wrist rehabilitation.
5. Develop a simple computer game to be used with the device.
6. Analyse the performance of the joystick and evaluate its effectiveness as a rehabilitation device.

As time permits:

7. Research, construct and implement a force-feedback system for the therapy device.

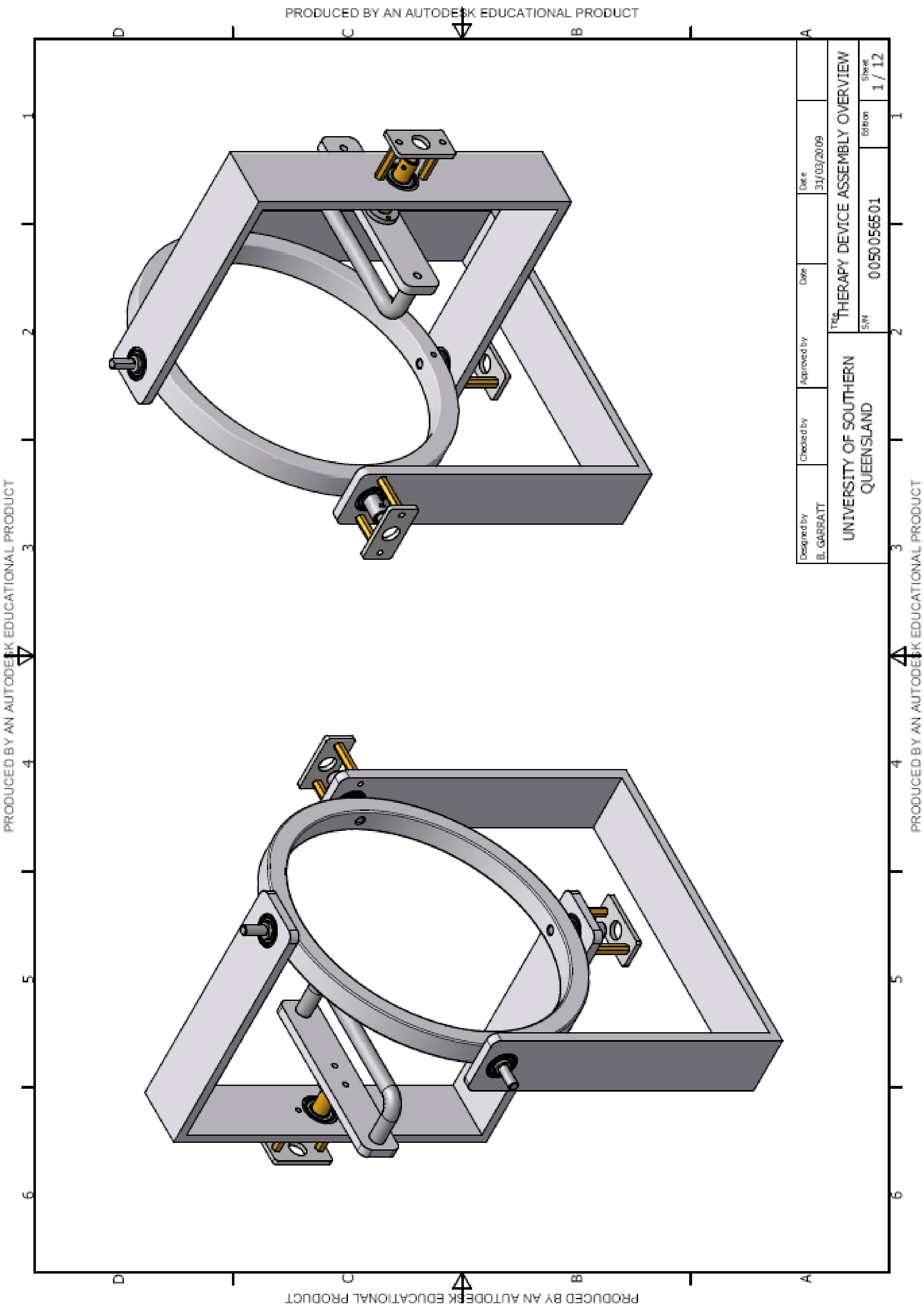
AGREED: ______ (Student) 25/5/09 ______ (Supervisor) 25/5/09

Examiner/Co-examiner: ______

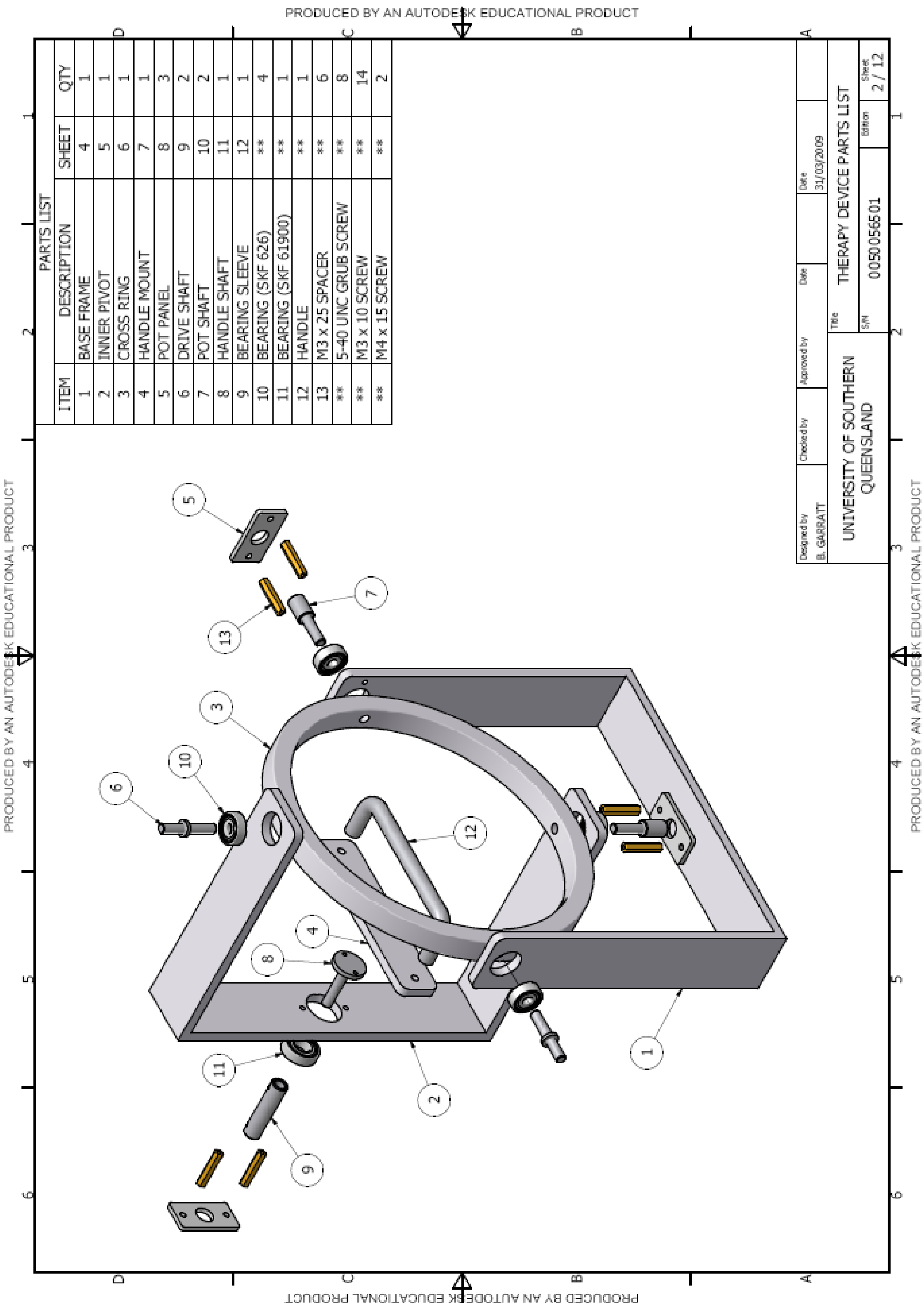
APPENDIX B DESIGN DRAWINGS

Appendix B contains all of the detailed design drawings submitted to the USQ for manufacture of the device. The drawings are not their original size and have been scaled down from A3 to fit in the Appendix.

B.1 Therapy Device Assembly Overview

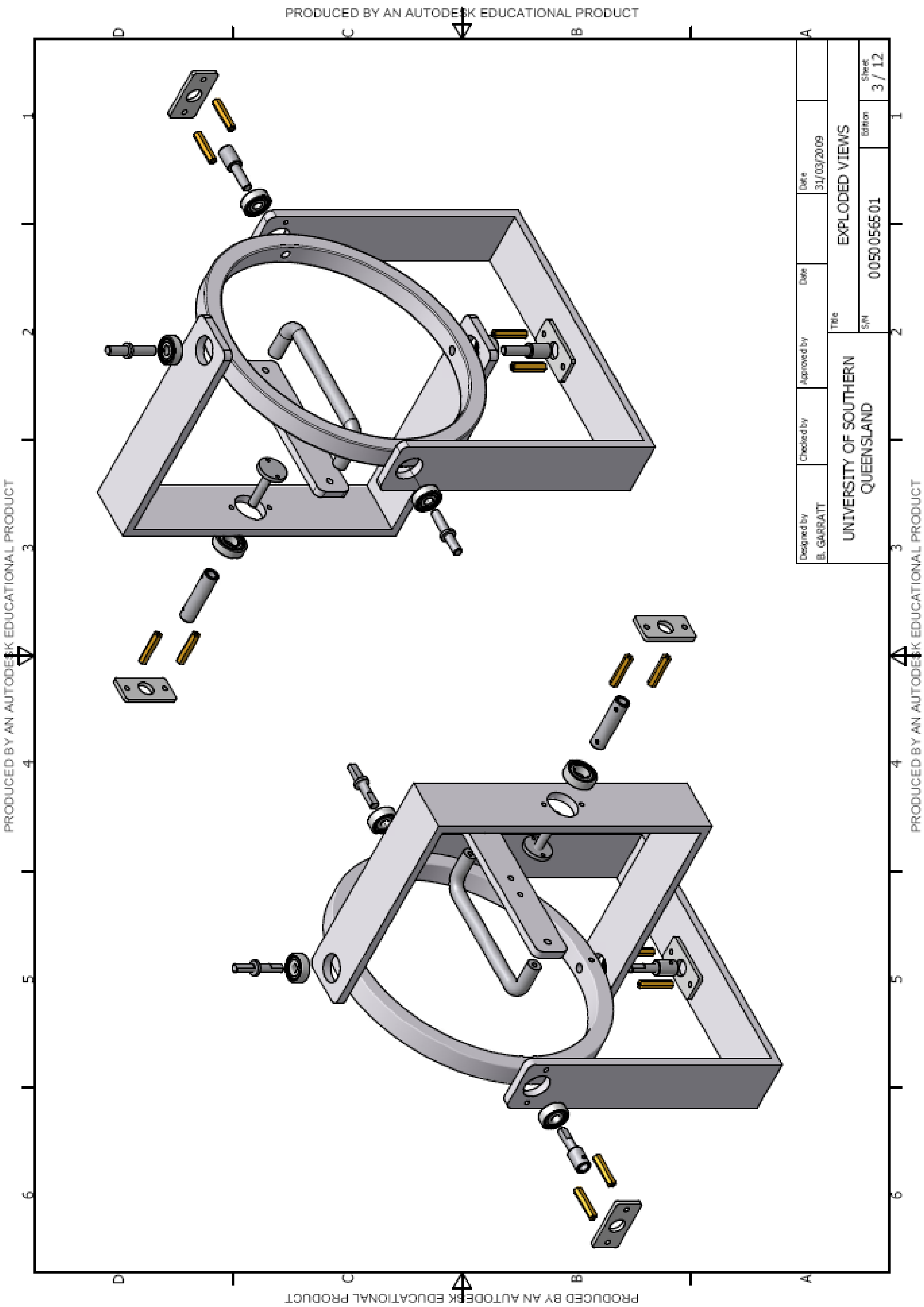


B.2 THERAPY DEVICE PARTS LIST

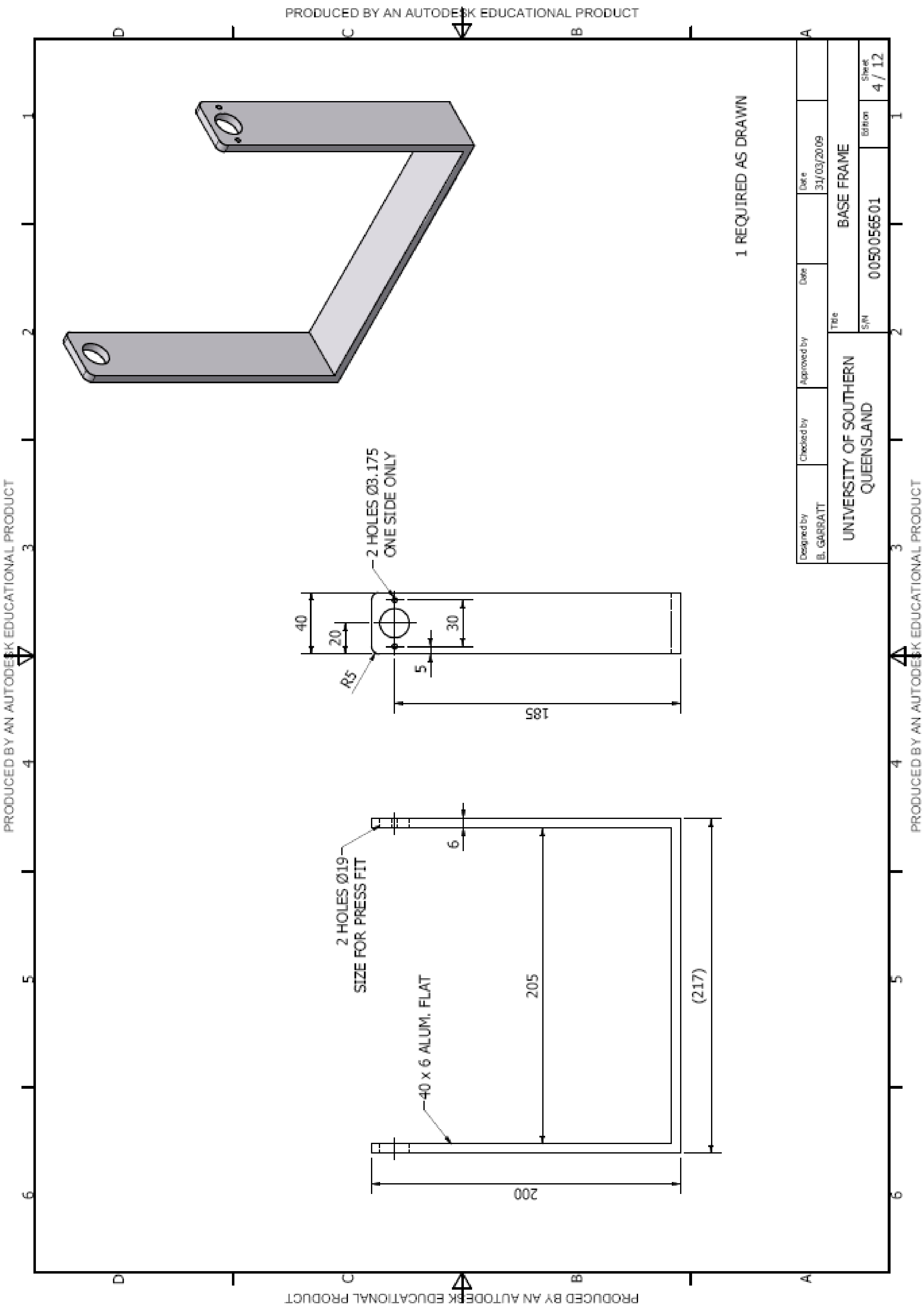


ITEM	DESCRIPTION	SHEET	QTY
1	BASE FRAME	4	1
2	INNER PIVOT	5	1
3	CROSS RING	6	1
4	HANDLE MOUNT	7	1
5	POT PANEL	8	3
6	DRIVE SHAFT	9	2
7	POT SHAFT	10	2
8	HANDLE SHAFT	11	1
9	BEARING SLEEVE	12	1
10	BEARING (SKF 626)	**	4
11	BEARING (SKF 61900)	**	1
12	HANDLE	**	1
13	M3 x 25 SPACER	**	6
**	5-40 UNC GRUB SCREW	**	8
**	M3 x 10 SCREW	**	14
**	M4 x 15 SCREW	**	2

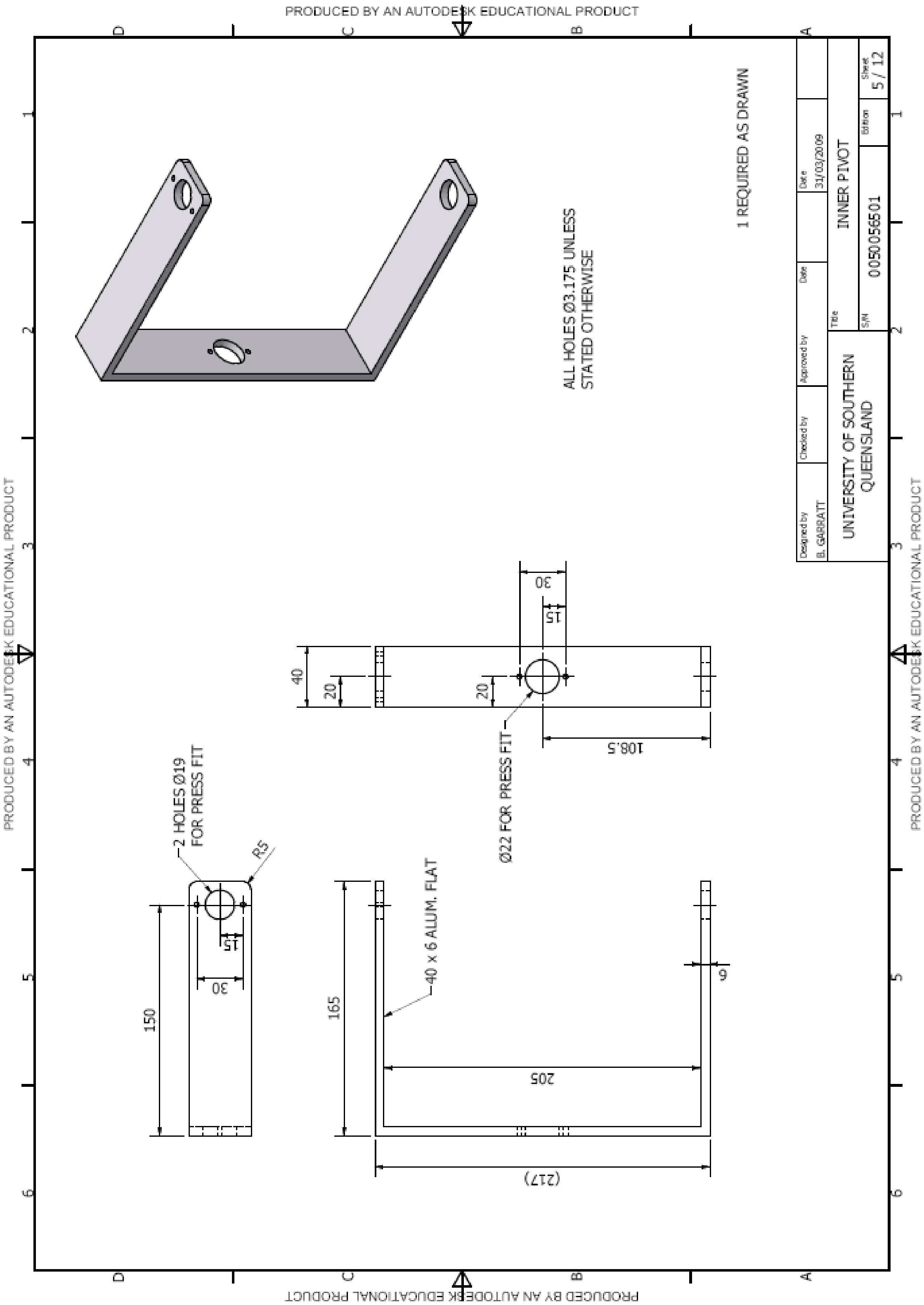
B.3 EXPLODED VIEWS



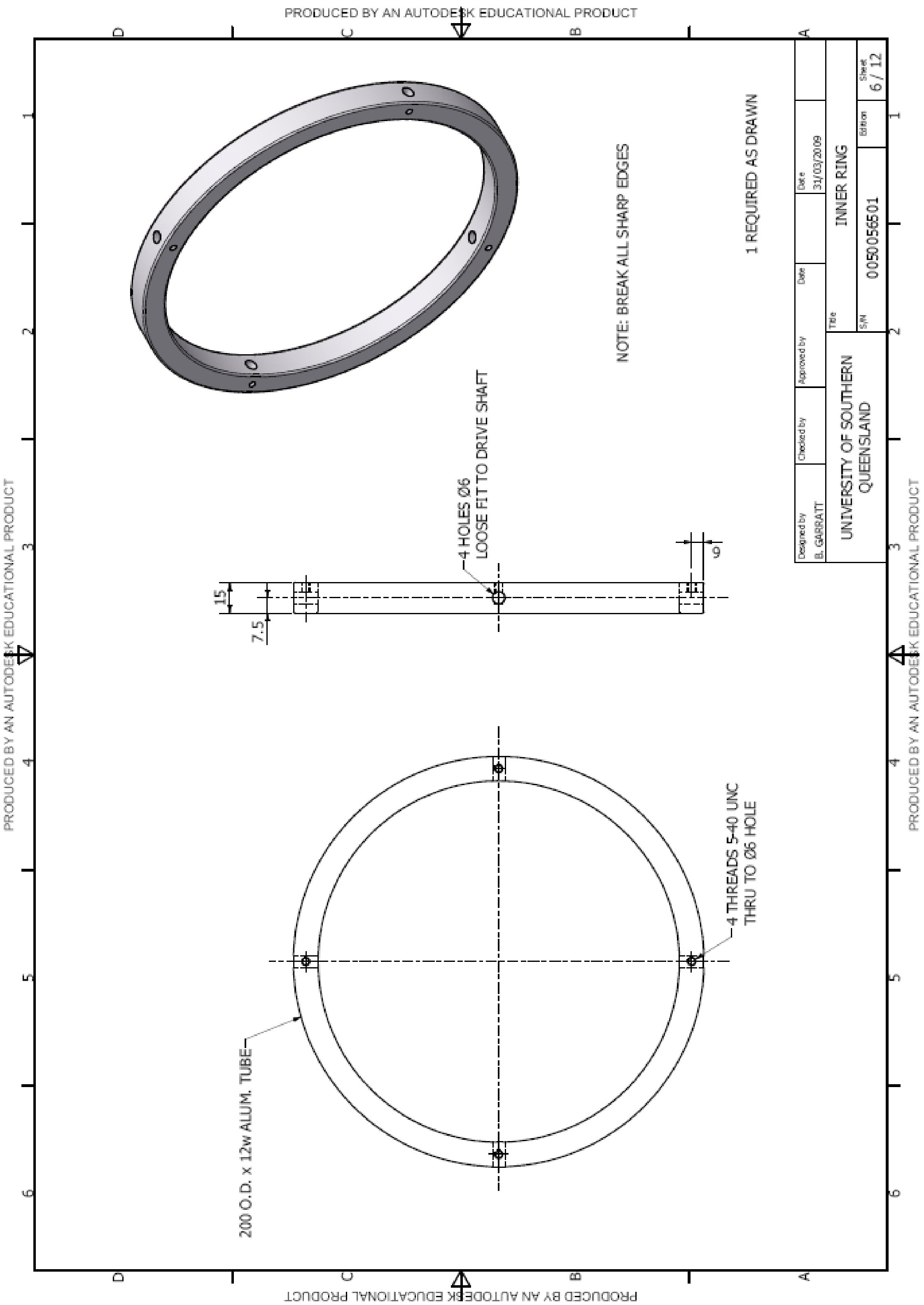
B.4 BASE FRAME



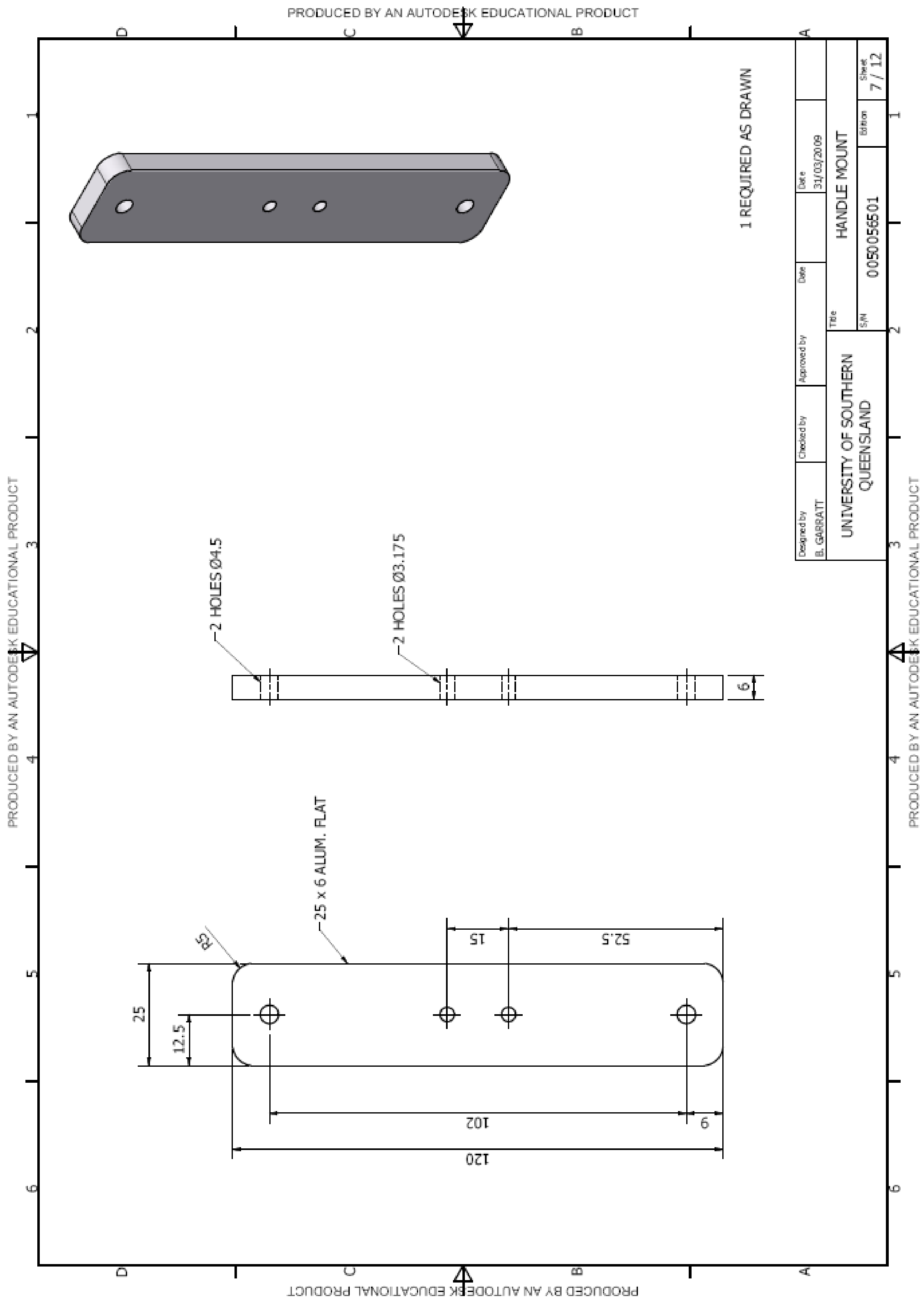
B.5 Pivot Fork



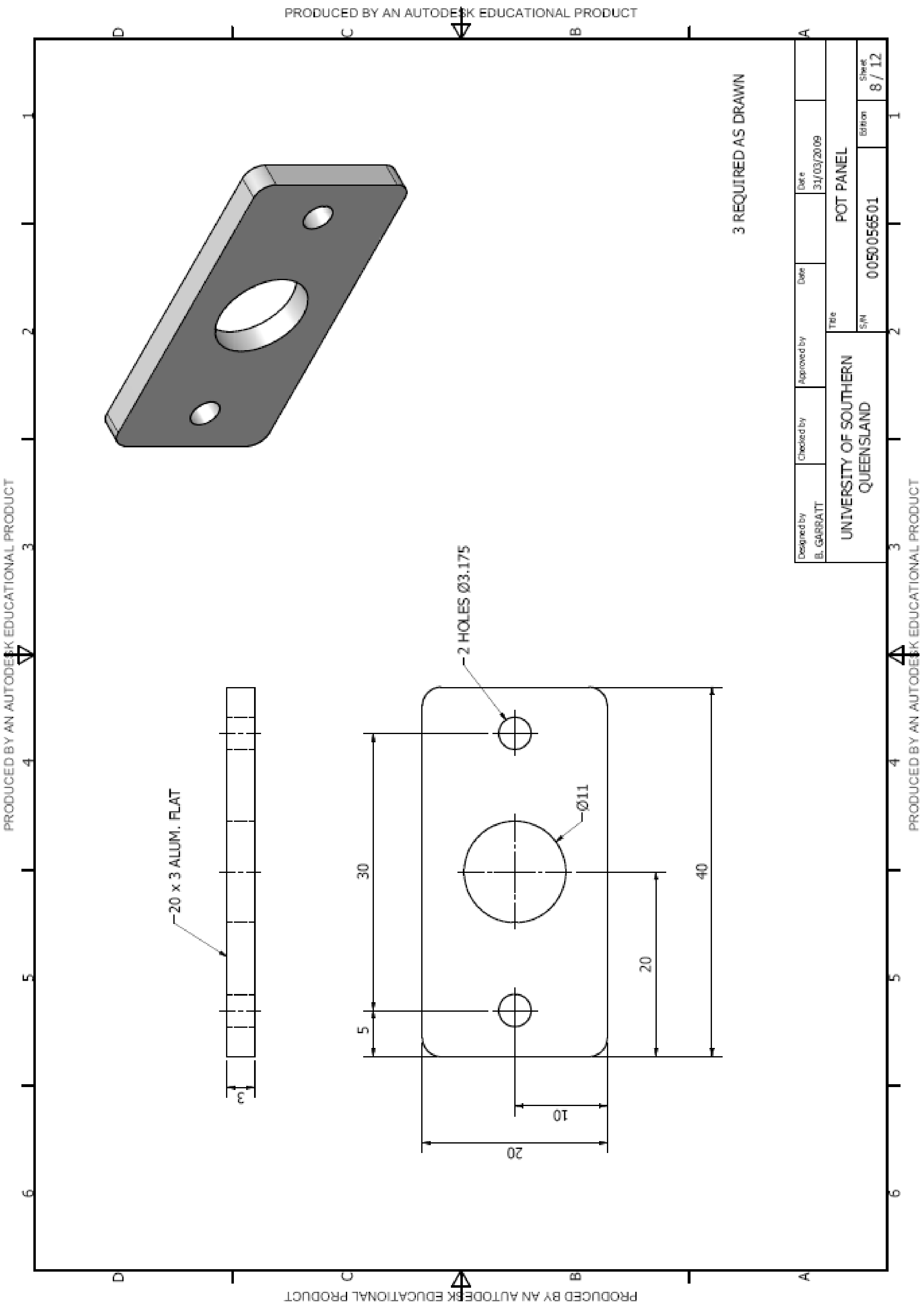
B.6 CROSS RING



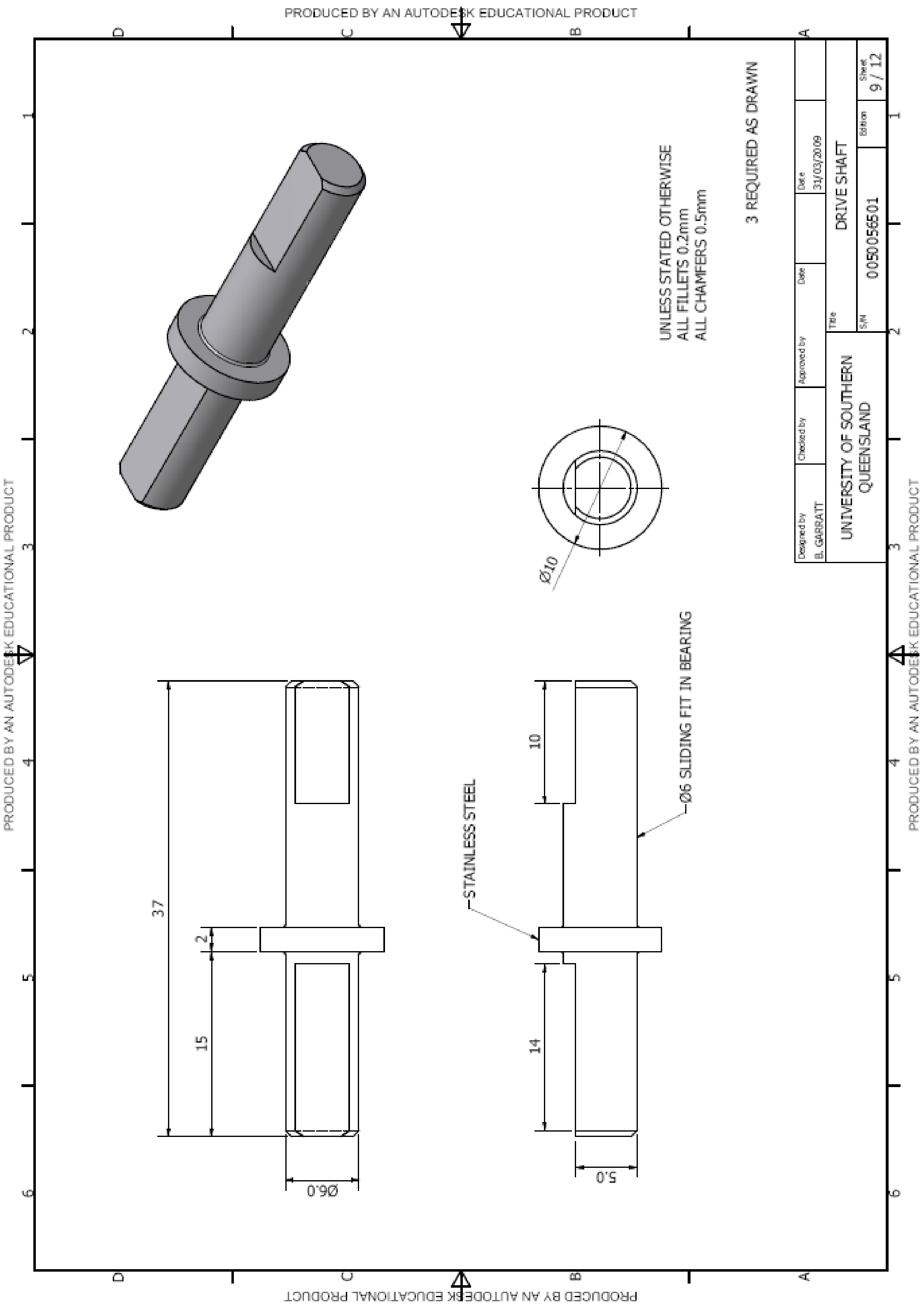
B.7 Handle Mount



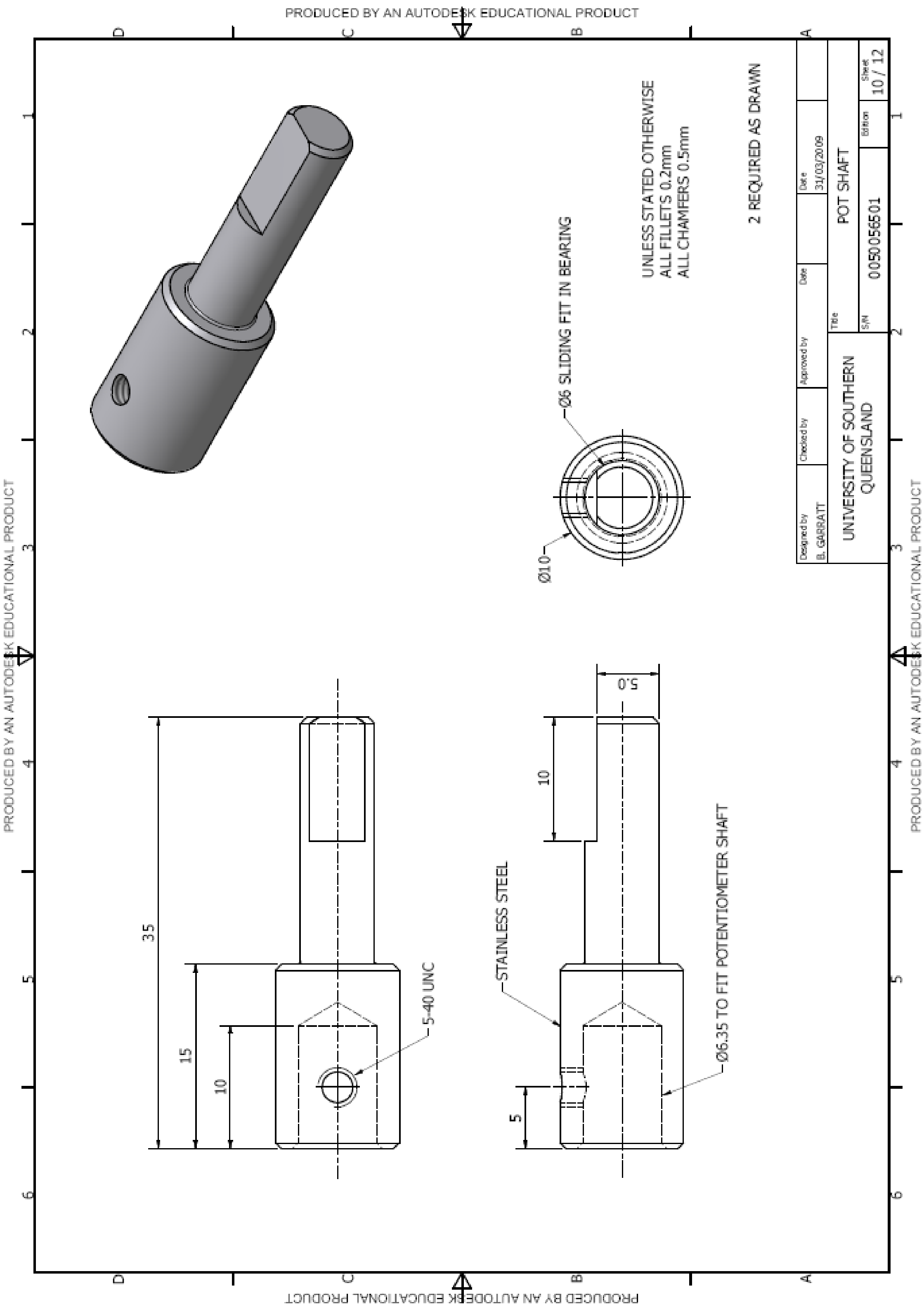
B.8 Pot Mounting Panel



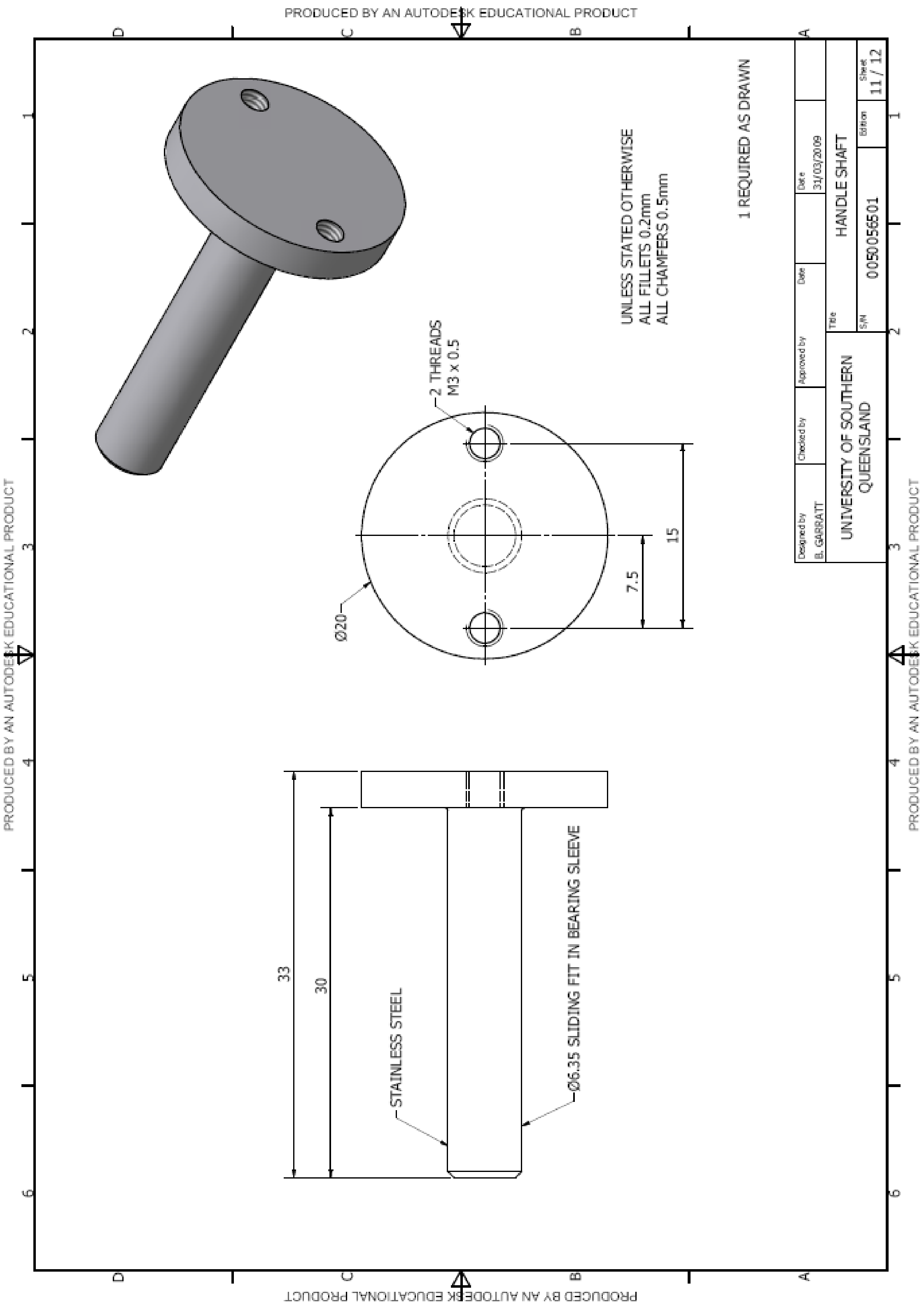
B.9 DRIVE SHAFT



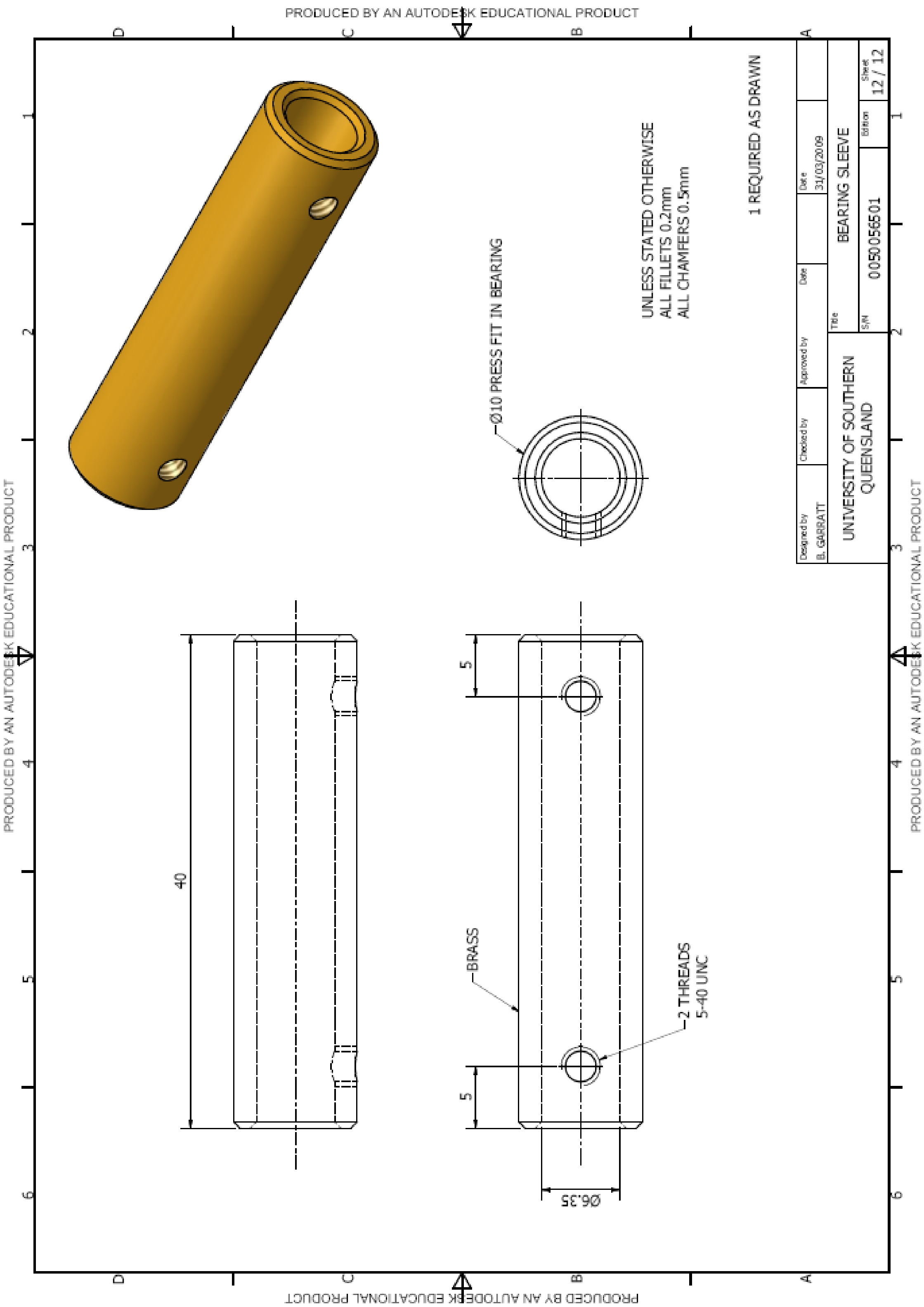
B.10 POT SHAFT



B.11 HANDLE SHAFT



B.12 Bearing Sleeve



APPENDIX C SOFTWARE CODE

This appendix contains full code listings of the software for the microcontroller and the computer.

C.1 MICROCONTROLLER CODE

```
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'This software is designed for use with the wrist rehabilitation'
'device.  The purpose of the software is to read analogue       '
'voltages on the pots, update the LCD display and send the data '
'to the computer.                                               '
'Author: Blythe Garratt                                         '
'Year:   2009                                                   '
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
Define CONF_WORD = 0x3f72
Define CLOCK_FREQUENCY = 20

'Define lcd display data lines
Define LCD_BITS = 4
Define LCD_DREG = PORTD
Define LCD_DBIT = 4
Define LCD_RSREG = PORTD
Define LCD_RSBIT = 0
Define LCD_RWREG = PORTD
Define LCD_RWBIT = 1
Define LCD_EREG = PORTD
Define LCD_EBIT = 2
Define LCD_READ_BUSY_FLAG = 1

'Define variable types
'Raw adc values
Dim xraw As Word
Dim yraw As Word
Dim zraw As Word
'Relative values
Dim xrel As Word
Dim yrel As Word
Dim zrel As Word
'Calibration values
Dim xset As Word
Dim yset As Word
Dim zset As Word
'Angle values
Dim xangle As Long
Dim yangle As Long
Dim zangle As Long
'Display mode
Dim mode As Byte
'Positive flags
Dim xpos As Bit
Dim ypos As Bit
Dim zpos As Bit
'Button flags
Dim but1_pressed As Bit
Dim but2_pressed As Bit
'Timer value
Dim timer1 As Word
timer1 = 40536  'for 20ms delay

'Define symbols
Symbol but1 = PORTB.5  'button 1
Symbol but2 = PORTB.4  'button 2
Symbol green_led = PORTB.2  'green led
Symbol red_led = PORTB.1  'red led
Symbol backlight = PORTD.3  'lcd backlight
```

```
'Start of program
start:
AllDigital
'Initialise lcd and custom characters
Lcdinit
Lcddefchar 0, 0x1c, 0x14, 0x1c, 0x00, 0x00, 0x00, 0x00, 0x00  'degree
symbol
'Initialise analogue port
ADCON1 = %10000100
'Initialise ports
TRISA = %11111111
TRISB = %11111001
TRISC = %10111111
TRISD = %00000000
'Set Timer registers
T1CON = %00100001
'Set interrupt registers
INTCON.TMR0IE = 0  'no interrupt on timer0
INTCON.GIE = 0  'disable global interrupt
Hseropen 56000  'initialise serial communication
green_led = 1  'turn green led on
red_led = 0  'turn red led off
'Print splash screen to LCD
backlight = 1
Lcdcmdout LcdClear
Lcdout "Wrist Therapy"
Lcdcmdout LcdLine2Home
Lcdout "Device  BJG 2009"
WaitMs 3000

'main program
      Gosub restore  'restore calibration values and menu state
main:
      While PIR1.TMR1IF = 0
      Wend
      TMR1H = timer1.HB
      TMR1L = timer1.LB
      PIR1.TMR1IF = 0  'reset timer flag
      Gosub measure  'perform ADC conversions
      Gosub convert
      Gosub buttons  'check if buttons are pressed
      Gosub display  'print results to lcd
      Gosub serial  'send data to computer
      Goto main  'start again
End

'restore calibration values and menu state
restore:
'Restore zero settings and display mode from EEPROM
Read 0, xset.HB
Read 1, xset.LB
Read 2, yset.HB
Read 3, yset.LB
Read 4, zset.HB
Read 5, zset.LB
Read 6, mode
'check that data is valid or use defaults
If mode > 2 Then
mode = 0
Endif
If xset > 1024 Then
xset = 0
Endif
```

```
If yset > 1024 Then
yset = 0
Endif
If zset > 1024 Then
zset = 0
Endif
Return
'Perform analogue to digital conversions
measure:
      zraw = 0
      xraw = 0
      yraw = 0
      Adcin 0, zraw
      Adcin 1, xraw
      Adcin 3, yraw
Return

'Send data serially to computer
serial:
      Hserout "x"
      If xpos = 0 Then
      Hserout "-"
      Endif
      Hserout #xrel, "y"
      If ypos = 0 Then
      Hserout "-"
      Endif
      Hserout #yrel, "z"
      If zpos = 0 Then
      Hserout "-"
      Endif
      Hserout #zrel, Lf
Return

'Update lcd display
display:
      Lcdcmdout LcdClear  'clear the lcd
      'Print menu options
      Lcdcmdout LcdLine1Pos(16)
      Lcdout "M"
      Lcdcmdout LcdLine2Pos(16)
      Lcdout "S"
      Lcdcmdout LcdLine1Home
      Select Case mode
      'Display the raw adc values
      Case 0
            Lcdout "X: ", #xraw
            Lcdcmdout LcdLine1Pos(9)
            Lcdout "Y: ", #yraw
            Lcdcmdout LcdLine2Home
            Lcdout "Z: ", #zraw
      'Display the raw difference from the zero position
      Case 1
            Lcdout "X:"
            If xpos = 0 Then
            Lcdout "-"
            Else
            Lcdout " "
            Endif
            Lcdout #xraw
            Lcdcmdout LcdLine1Pos(8)
            Lcdout "Y:"
            If ypos = 0 Then
```

```
            Lcdout "-"
            Else
            Lcdout " "
            Endif
            Lcdout #yraw
            Lcdcmdout LcdLine2Home
            Lcdout "Z:"
            If zpos = 0 Then
            Lcdout "-"
            Else
            Lcdout " "
            Endif
            Lcdout #zraw
      'Display the angle in degrees from zero position
      Case 2
            'Convert raw adc values to angle
            Lcdout "X:"
            If xpos = 0 And xangle > 0 Then
            Lcdout "-"
            Else
            Lcdout " "
            Endif
            Lcdout #xangle.LW, 0
            Lcdcmdout LcdLine1Pos(8)
            Lcdout "Y:"
            If ypos = 0 And yangle > 0 Then
            Lcdout "-"
            Else
            Lcdout " "
            Endif
            Lcdout #yangle.LW, 0
            Lcdcmdout LcdLine2Home
            Lcdout "Z:"
            If zpos = 0 And zangle > 0 Then
            Lcdout "-"
            Else
            Lcdout " "
            Endif
            Lcdout #zangle.LW, 0
      EndSelect
      Toggle green_led
      Toggle red_led
Return

'Poll the buttons
buttons:
      If but1 = 0 Then  'check if button is down
            but1_pressed = 1
            Else  'button not being pressed
            If but1_pressed = 1 Then  'button has been released
                  mode = mode + 1
                  mode = mode Mod 3
                  but1_pressed = 0  'reset button status
            Endif
      Endif
      If but2 = 0 Then  'check if button is down
            but2_pressed = 1
            Else  'button not being pressed
            If but2_pressed = 1 Then  'button has been released
                  xset = xraw
                  yset = yraw
                  zset = zraw
                  Write 0, xset.HB
```

```
                  Write 1, xset.LB
                  Write 2, yset.HB
                  Write 3, yset.LB
                  Write 4, zset.HB
                  Write 5, zset.LB
                  Write 6, mode
                  but2_pressed = 0  'reset button status
            Endif
      Endif
Return

'Convert raw results to rotations
convert:
      xrel = xraw - xset
      yrel = yraw - yset
      zrel = zraw - zset
      If xrel > 1024 Then
                  xrel = 65535 - xrel + 1
                  xpos = 0
            Else
                  xpos = 1
      Endif
      If yrel > 1024 Then
                  yrel = 65535 - yrel + 1
                  ypos = 0
            Else
                  ypos = 1
      Endif
      If zrel > 1024 Then
                  zrel = 65535 - zrel + 1
                  zpos = 0
            Else
                  zpos = 1
      Endif
      xangle = 340 * xrel / 1023
      yangle = 340 * yrel / 1023
      zangle = 340 * zrel / 1023
Return
```

C.2 PC Code

C.2.1 Main Application.VB

```
Imports Microsoft.VisualBasic.PowerPacks
Imports System.Math
Public Class MainApplication
    Dim screensize As Size
    Dim relative = False
    Dim grid = True
    Dim gameon = False
    Dim testing = False
    Dim newtarget = True
    Dim gotocenter = True
    Dim xtarget As Integer
    Dim ytarget As Integer
    Dim targetrad As Integer = 16
    Dim target_ext As Integer = 40
    Dim target_flex As Integer = 40
    Dim target_add As Integer = 28
    Dim target_abd As Integer = 12
    Dim righthand As Boolean = True
    Dim coneext(180) As Decimal
    Dim coneflex(180) As Decimal
    Dim maxabs(180) As Decimal
    Dim minabs(180) As Decimal
    Dim maxcurve(180) As Point
    Dim mincurve(180) As Point


    Private Sub MainApplication_Load(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles MyBase.Load
        'Maximise window
        Me.WindowState = FormWindowState.Maximized
        Me.ResizeRedraw = True
        Me.SetStyle(ControlStyles.AllPaintingInWmPaint, True)
        Me.DoubleBuffered = True
        Me.SetStyle(ControlStyles.OptimizedDoubleBuffer, True)
        screensize = Me.Size
        RS232COM.Show()
    End Sub

    Private Sub MainApplication_Paint(ByVal sender As Object, ByVal e
As System.Windows.Forms.PaintEventArgs) Handles Me.Paint
        Dim xpos As Decimal
        Dim ypos As Decimal
        Dim zpos As Decimal
        Dim extension As Decimal
        Dim abduction As Decimal
        Dim pronation As Decimal
        Dim xtran As Decimal
        Dim ytran As Decimal
        Dim scalefactor As Integer
        Dim arrow = My.Resources.myarrow
        Dim gridpen As New Pen(Color.Black, 1)
        gridpen.DashStyle = Drawing2D.DashStyle.Dash
        Dim line As Integer
        Dim point1 As Point
        Dim point2 As Point
        scalefactor = screensize.Width / 200
        xpos = Val(RS232COM.xPOT.Text) * 340 / 1023
        ypos = Val(RS232COM.yPOT.Text) * 340 / 1023
```

```
        zpos = Val(RS232COM.zPOT.Text) * 340 / 1023

        'Calculate onscreen translations
        If relative = True Then
            If righthand = True Then
                extension = xpos * Cos(zpos * PI / 180) - ypos *
Sin(zpos * PI / 180)
                abduction = ypos * Cos(zpos * PI / 180) + xpos *
Sin(zpos * PI / 180)
                pronation = zpos
            Else
                extension = -xpos * Cos(zpos * PI / 180) + ypos *
Sin(zpos * PI / 180)
                abduction = ypos * Cos(zpos * PI / 180) + xpos *
Sin(zpos * PI / 180)
                pronation = -zpos
            End If

            xtran = screensize.Width / 2 + extension * scalefactor
            ytran = screensize.Height / 2 - abduction * scalefactor
            xlabel.Text = Round(abduction, 2) & "°"
            ylabel.Text = Round(extension, 2) & "°"
            zlabel.Text = Round(zpos, 2) & "°"
        Else
            xtran = screensize.Width / 2 + xpos * scalefactor
            ytran = screensize.Height / 2 - ypos * scalefactor
            xlabel.Text = Round(xpos, 2) & "°"
            ylabel.Text = Round(ypos, 2) & "°"
            zlabel.Text = Round(zpos, 2) & "°"
        End If

        'Draw grid if selected
        If grid = True Then
            'Draw vertical grid lines
            For line = -10 To 10
                point1.X = screensize.Width / 2 - 10 * scalefactor *
line
                point1.Y = 0
                point2.X = point1.X
                point2.Y = screensize.Height
                If line = 0 Then
                    e.Graphics.DrawLine(New Pen(Color.Black, 2),
point1, point2)
                Else
                    e.Graphics.DrawLine(gridpen, point1, point2)
                End If
            Next line
            'Draw horizontal grid lines
            For line = -9 To 9
                point1.X = 0
                point1.Y = screensize.Height / 2 - 10 * scalefactor *
line
                point2.X = screensize.Width
                point2.Y = point1.Y
                If line = 0 Then
                    e.Graphics.DrawLine(New Pen(Color.Black, 2),
point1, point2)
                Else
                    e.Graphics.DrawLine(gridpen, point1, point2)
                End If
            Next line
        End If
```

```
        'Enable high quality antialiasing
        e.Graphics.SmoothingMode = Drawing2D.SmoothingMode.AntiAlias

        'Render game graphics
        If gameon = True Then
            If newtarget = True Then
                If gotocenter = True Then
                    xtarget = screensize.Width / 2
                    ytarget = screensize.Height / 2
                Else
                    'Generate a random target within maximum motion
ranges
                    xtarget = (screensize.Width / 2) - scalefactor *
(CInt(Int(((target_ext + target_flex) * Rnd()) + 1)) - target_flex)
                    ytarget = (screensize.Height / 2) - scalefactor *
(CInt(Int(((target_abd + target_add) * Rnd()) + 1)) - target_add)
                End If
                newtarget = False
            End If
            e.Graphics.DrawEllipse(New Pen(Color.Green, 3), xtarget -
targetrad, ytarget - targetrad, targetrad * 2, targetrad * 2)
            If (xtran - xtarget) ^ 2 + (ytran - ytarget) ^ 2 <
targetrad ^ 2 Then
                newtarget = True
                gotocenter = Not (gotocenter)
            End If
        End If

        'Range of mode testing
        If testing = True Then
            'Record maximum and minimum abduction for each degree of
extension
            If abduction > maxabs(CInt(extension) + 90) Then
                maxabs(CInt(extension) + 90) = abduction

            ElseIf abduction < minabs(CInt(extension) + 90) Then
                minabs(CInt(extension) + 90) = abduction
            End If
            For i = 0 To 180
                maxcurve(i) = New Point(screensize.Width / 2 + (i -
90) * scalefactor, screensize.Height / 2 - CInt(maxabs(i)) *
scalefactor)
                mincurve(i) = New Point(screensize.Width / 2 + (i -
90) * scalefactor, screensize.Height / 2 - CInt(minabs(i)) *
scalefactor)
            Next

            'Plot the cone of circumduction
            e.Graphics.DrawPolygon(New Pen(Color.Black, 3), maxcurve)
            e.Graphics.DrawPolygon(New Pen(Color.Black, 3), mincurve)
        End If

        'Transform target image from top left pixel
        e.Graphics.TranslateTransform(xtran, ytran)
        e.Graphics.RotateTransform(zpos)


        'Draw target image at correct position
        e.Graphics.DrawLine(New Pen(Color.Red, 2), -32, 0, 32, 0)
        e.Graphics.DrawLine(New Pen(Color.Red, 2), 0, -32, 0, 32)
        e.Graphics.DrawLine(New Pen(Color.Red, 2), 0, -32, 8, -16)
        e.Graphics.DrawLine(New Pen(Color.Red, 2), 0, -32, -8, -16)
```

```
        e.Graphics.DrawEllipse(New Pen(Color.DarkBlue, 2), -32, -32, 
64, 64)

    End Sub

    Private Sub MainApplication_Resize(ByVal sender As Object, ByVal 
e As System.EventArgs) Handles Me.Resize
        screensize = Me.Size
    End Sub

    Private Sub ExitToolStripMenuItem1_Click(ByVal sender As 
System.Object, ByVal e As System.EventArgs) Handles 
ExitToolStripMenuItem1.Click
        RS232COM.Close()
        Me.Close()
    End Sub

    Private Sub PlayToolStripMenuItem_Click(ByVal sender As 
System.Object, ByVal e As System.EventArgs) Handles 
PlayToolStripMenuItem.Click
        gameon = True
        PlayToolStripMenuItem.Checked = True
        FreeMove_TSM.Checked = False
    End Sub

    Private Sub StopToolStripMenuItem_Click(ByVal sender As 
System.Object, ByVal e As System.EventArgs) Handles 
StopToolStripMenuItem.Click
        gameon = False
        PlayToolStripMenuItem.Checked = False
    End Sub

    Private Sub Easy_TSM_Click(ByVal sender As System.Object, ByVal e 
As System.EventArgs) Handles Easy_TSM.Click
        targetrad = 32
        Easy_TSM.Checked = True
        Medium_TSM.Checked = False
        Hard_TSM.Checked = False
    End Sub

    Private Sub Medium_TSM_Click(ByVal sender As System.Object, ByVal 
e As System.EventArgs) Handles Medium_TSM.Click
        targetrad = 16
        Easy_TSM.Checked = False
        Medium_TSM.Checked = True
        Hard_TSM.Checked = False
    End Sub

    Private Sub Hard_TSM_Click(ByVal sender As System.Object, ByVal e 
As System.EventArgs) Handles Hard_TSM.Click
        targetrad = 8
        Easy_TSM.Checked = False
        Medium_TSM.Checked = False
        Hard_TSM.Checked = True
    End Sub

    Private Sub Flexion_Text_Enter(ByVal sender As Object, ByVal e As 
System.EventArgs) Handles Flexion_Text.Enter
        target_flex = Flexion_Text.Text
    End Sub

    Private Sub Ext_text_Enter(ByVal sender As Object, ByVal e As 
System.EventArgs) Handles Ext_text.Enter
```

```
        target_ext = Ext_text.Text
    End Sub

    Private Sub Adb_Text_Enter(ByVal sender As Object, ByVal e As
System.EventArgs) Handles Adb_Text.Enter
        target_abd = Adb_Text.Text
    End Sub

    Private Sub Add_Text_Enter(ByVal sender As Object, ByVal e As
System.EventArgs) Handles Add_Text.Enter
        target_abd = Add_Text.Text
    End Sub

    Private Sub RHand_TSM_Click(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles RHand_TSM.Click
        RHand_TSM.Checked = True
        LHand_TSM.Checked = False
        righthand = True
    End Sub

    Private Sub LHand_TSM_Click(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles LHand_TSM.Click
        RHand_TSM.Checked = False
        LHand_TSM.Checked = True
        righthand = False
    End Sub

    Private Sub FreeMove_TSM_Click(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles FreeMove_TSM.Click
        gameon = False
        testing = False
        PlayToolStripMenuItem.Checked = False
        FreeMove_TSM.Checked = True
    End Sub

    Private Sub RangeOfMotionToolStripMenuItem1_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RangeOfMotionToolStripMenuItem1.Click
        testing = True
        gameon = False
        RangeOfMotionToolStripMenuItem1.Checked = True
        PlayToolStripMenuItem.Checked = False
        FreeMove_TSM.Checked = False

    End Sub

    Private Sub OnToolStripMenuItem_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
OnToolStripMenuItem.Click
        OnToolStripMenuItem.Checked = True
        OffToolStripMenuItem.Checked = False
        grid = True
        Refresh()
    End Sub

    Private Sub OffToolStripMenuItem_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
OffToolStripMenuItem.Click
        OnToolStripMenuItem.Checked = False
        OffToolStripMenuItem.Checked = True
        grid = False
        Refresh()
    End Sub
```

```
    Private Sub WristToolStripMenuItem_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
WristToolStripMenuItem.Click
        WristToolStripMenuItem.Checked = True
        DeviceToolStripMenuItem.Checked = False
        ssxlabel.Text = "Abduction:"
        ssylabel.Text = "Extension:"
        sszlabel.Text = "Pronation:"
        relative = True
    End Sub

    Private Sub DeviceToolStripMenuItem_Click(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
DeviceToolStripMenuItem.Click
        WristToolStripMenuItem.Checked = False
        DeviceToolStripMenuItem.Checked = True
        ssxlabel.Text = "XPOT:"
        ssylabel.Text = "YPOT:"
        sszlabel.Text = "ZPOT:"
        relative = False
    End Sub



End Class
```

C.2.2 RS232COM.VB

```
Public Class RS232COM
    Dim WithEvents serialPort As New IO.Ports.SerialPort


    Private Sub RS232COM_FormClosing(ByVal sender As Object, ByVal e
As System.Windows.Forms.FormClosingEventArgs) Handles Me.FormClosing
        If serialPort.IsOpen = True Then
            serialPort.Close()
        End If
    End Sub


    Private Sub RS232(ByVal sender As System.Object, ByVal e As
System.EventArgs) _
    Handles MyBase.Load
        'If serial port is active close it so transfer protocols can
be established
        If serialPort.IsOpen Then
            serialPort.Close()
        End If
        'Define transfer protocols
        While serialPort.IsOpen = 0
            Try
                serialPort.PortName = "COM1"
                serialPort.BaudRate = 56000
                serialPort.Parity = IO.Ports.Parity.None
                serialPort.DataBits = 8
                serialPort.StopBits = IO.Ports.StopBits.One
                serialPort.ReadTimeout = 200
                serialPort.Open()
            Catch ex As Exception
                MsgBox("Please connect device and press OK.")
            End Try
        End While
    End Sub

    Private Sub DataReceived(ByVal sender As Object, ByVal e As
System.IO.Ports.SerialDataReceivedEventArgs) Handles
serialPort.DataReceived
        'Get data sentence from COM1 port
        Dim Buffer As String
        Try
            Buffer = serialPort.ReadLine()
            Me.BeginInvoke(New StringSubPointer(AddressOf Display),
serialPort.ReadLine())
        Catch ex As Exception
        End Try

    End Sub

    Public Delegate Sub StringSubPointer(ByVal Buffer As String)
    Public Sub Display(ByVal Buffer As String)
        Dim x_char_pos As Byte
        Dim y_char_pos As Byte
        Dim z_char_pos As Byte
        Dim num_chars As Byte
        'Determine length of string and positions of marker
characters
        num_chars = Buffer.Length
        x_char_pos = Buffer.IndexOf("x")
        y_char_pos = Buffer.IndexOf("y")
```

```
        z_char_pos = Buffer.IndexOf("z")
        'Check that the data string is valid
        If x_char_pos = 0 And (x_char_pos < y_char_pos < z_char_pos)
Then
            ReceiveData.Text = Buffer
            xPOT.Text = Buffer.Substring(x_char_pos + 1, y_char_pos -
x_char_pos - 1)
            yPOT.Text = Buffer.Substring(y_char_pos + 1, z_char_pos -
y_char_pos - 1)
            zPOT.Text = Buffer.Substring(z_char_pos + 1, num_chars -
z_char_pos - 1)
            MainApplication.Refresh()
        Else
            ReceiveData.Text = "ERROR"
        End If
    End Sub

End Class
```