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University of Southern Queensland

Faculty of Engineering and Surveying

DEVELOPMENT OF
A DRIVER TRAINING SIMULATOR
FOR USE BY STROKE PATIENTS

A dissertation submitted by

Geoffrey Mark O'Shannassy

in fulfilment of the requirements of

Courses ENG4111 And 4112 Research Project

towards the degree of

Bachelor of Engineering (Mechatronics)

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Abstract

Stroke will affect around 60,000 people in 2009 with up to 40000 of those losing the ability to drive. This loss of independence and mobility can have a severe impact on their quality of life and emotional well being.

Traditional methods of stroke rehabilitation are often therapist intensive or boring and repetitive. Robotic and semi-robotic devices for stroke rehabilitation are in their infancy with very few devices readily available in clinics and even less available in homes. The method of driver retraining relies on the therapist taking the patient *"back on the road",* an often hair-raising and potentially dangerous task.

A fully developed force feedback steering wheel and driving simulator for stroke patients has great potential for reducing therapist contact hours and increasing the effectiveness of driver retraining.

The project aims to design, construct and test a force feedback steering wheel that is :-

- suitable for use as a tool in the assessment and retraining of stroke patients.
- simple enough for both clinical and in-home use.
- able to provide sufficient torque for passive resistance, active resistance, and active assistance.
- able to record user inputs as an aid to assessment and progress of driving ability

Both the mechanical and electronic systems have been constructed. Torque is provided by a 100W 24V permanent magnet DC motor, connected to the steering shaft by a toothed belt with a gear ratio of 8.4:1. The motor is controlled via a PIC micro embedded microcontroller running custom written software while power amplification is handled by a 1 KW H-bridge motor control.

In general, the testing and evaluation of the device has been promising, this is especially so in the overall feel of the device and the ability to control or vary the feel. Importantly the device has been successfully interfaced to the PC and is able to interact with a simple game environment. While some problems have been encountered a number of strategies have been devised to overcome these problems.

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I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Geoffrey Mark O'Shannassy

Student Number: 0011121004

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I would like to express my most sincere thanks and gratitude to my wife Jodie and daughter Nicole have supported me throughout this project and put up with me when I was tired and cranky.

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Chapter 1 - Introduction

1.1 Introduction

Up to 60,000 Australians will suffer a first time or recurrent stoke in 2009 according to a report by The Stroke Foundation of Australia. With Australia's aging population that that number is set to increase over the next few years. Some 88% of stroke survivors live at home, most with some level of disability. The level of disability varies greatly depending on the severity of the stroke. Effects range from weakness, paralysis, loss of perception (touch or sight), depression, tiredness, incontinence, ability to read, write or speak, and cognitive impairment (the ability to think, reason or problem solve.)

The direct effects of stroke can have a much wider impact on the patients' lifestyle and self sufficiency than is immediately apparent. The patient may lose the ability to undertake a number of different tasks ranging, from feeding, dressing, attending to personal needs, walking, communicating or driving. Each of these in turn further has a further impact on the patients' quality of life.

The use of haptic devices in stroke rehabilitation has great potential, both through increase patient motivation towards rehabilitation exercises and some lightning of the load on rehabilitation staff. This project focuses on the use of driving simulators in rehabilitation as a safer more accessible means of driver retraining after stroke and seeks to develop a simulator suitable for use in that field

1.2 Problem Definition

One of the most significant and impacting activities affected is the ability to drive with around 60-70% of stroke survivors in Australia no longer able to continue driving. Loss of driving ability has a cascading effect on other activities normally engaged in such as shopping, social engagement or any other activity undertaken outside the home. Research by Patomella, Johannson and Tham (2005), has shown that the loss of driving ability can have a severe impact on the mental, emotional and social well being of stroke patients. Upon receiving the news that they are no longer able to drive,

reactions range, from a sense of violation, anger, sadness, anxiety or even complete denial and a continuation of driving albeit unsafely.
In a recent study by Lannin & McCluskey (2008) revealed that the inability to drive following a stroke was the fourth most significant factor in stroke patients experiencing social isolation. A recent survey showed that as little as 30% – 40% of stroke survivors resumed driving.

Four key areas, divided between patients and rehabilitation staff, can be identified as problematic with regard to stroke patients' loss of driving ability.
They are:

1. The direct and indirect impacts of ceasing to drive on stroke patients
2. A lack of awareness or denial of the loss of driving skill following stroke
3. Driver Training and Assessment activity increases the workload of rehabilitation staff
4. Availability and usability of training and assessment tools

Retraining and assessment of driving ability frequently falls to occupational or stoke rehabilitation therapists many of whom are untrained or lack adequate training tools. This retraining represents a significant level of stress to the nurses who must take them on the road. With limited human resources, in the form of rehabilitation nurses, the task of returning to driving can easily become insurmountable for the patient.

Traditional driver retraining approaches have focused on cognitive type therapies to retrain patients in aspects of driving such as sign recognition before beginning on road training. Research by Akinwuntan (2005) has shown that such methods are less effective than the use of tools such as driving simulators that provide a learning environment close to or similar to the environment in which that activity normally takes place.

If a driving simulator system tailored to the retraining of stroke patients were available, as considerable load could be transferred from the nurses and onto machines. The system would have even more potential if it could be made available for use within the home providing a great opportunity for increased practice and training without a trip to hospital or a visit from a rehabilitation nurse. The benefit for nurses and physiotherapist is equally attractive with the ability to monitor patient progress, skill and road readiness.

S. Pather (2008, pers.comm., 20 February) noted the that the main skills deficits associated with stroke are, the tendency to overcorrect leading to swerving and a loss of reaction times to important events. He further noted that on road training is a considerable source of stress for rehabilitation staff, with virtually no other options. Development of rehabilitation aids that require minimum input and attention from therapist while maintaining patient interest are on the increase. Most of these however are still at a research level, or of such size cost and complexity that the commissioning of such equipment en-masse amongst rehabilitation clinics across Australia or any part of the developed world has simply not been possible.

In short a driving simulator has great potential to aid therapists in driver retraining. Simulators can not only lighten the work load but are also able to provide a safe environment while tracking patient progress and ability.

1.3 Project Objectives

This study aims to review the methods and effectiveness of mechanical type rehabilitation systems that incorporate the use of computer games or assessments with a particular focus on the use of driving simulators. The project aims to design construct and test a force feedback steering wheel suitable for use as a tool in the assessment and retraining of stroke patients. While the initial system is focused on development of a prototype it is hoped that future work can develop a system for use in rehabilitation clinics and eventually within homes.

The project also aims to investigate the possibility of using a current sensor to measure torque in conjunction with left or right biased tasks to determine if a person is better at either task with left or right limb.

An outline of specific project tasks is as follows :-

1. Research the use of computer games and haptic devices in the area of stroke patient rehabilitation specifically in the area of driving simulators.
2. Design and construct a force feedback steering wheel with the capability of providing passive resistance, active resistance and active assistance.
3. Select and implement the associated electronics for data collection, feedback application and interface to a Windows based PC.
4. Develop a software based position controller to provide passive resistance.
5. Design and code a simple computer game capable of taking measurements relevant to patient rehabilitation progress making raw data available for further processing.
6. Create a simple 2D driving simulator
7. Investigate and develop methods of providing active resistance and active assistance.
8. Implement in program data logging and analysis.

1.4 Methodology

The undertaking of type of project requires a methodical approach, as such a number of methodologies have been defined to give guidance to the project and are detailed here.

- Review Existing Stroke Based Simulators

In addition to an initial review of the types of driving simulators used in stroke therapies, an overview of other pc based rehabilitation systems and devices will be undertaken in an effort to transfer some of the most successful techniques into a driving simulator environment.

- Develop Conceptual Designs of the device and it's sub systems

A series of design concepts will be developed and evaluated, including various sub systems.

- Detailed Design and Construction of Mechanical System

The most suitable design and sub system concepts will be designed in detailed and modelled in a 3d computer environment. The 3d models created will be used to create detail drawing suitable for manufacture. Manufacture of these components will be undertaken by the USQ workshop. Design of the mechanical system also includes the selection of the feedback mechanism.

- Selection of Electronics Components

Several different electronic sub systems will be required. A PC to device interface is required for collecting sensor outputs and potentially to provide feedback control signals. Power amplification of control signals is necessary to provide feedback to the user. It is expected that some level of sensor output amplification or level shifting will be required to ensure it is within a suitable range for the interface circuitry. Electronic safety systems are necessary as a means of providing protection for the user. It is envisaged that this system will require a number input conditions to exist before power can be applied to the feedback mechanism.

- Selection of Software

A PC based programming software package is necessary for development of the game interface, data logging and reporting. Depending on the choice of interface electronics the PC may also be used to implement the control system and reading of sensors. The greatest benefit of this arrangement is the need to learn only one programming language. Alternately the use of a microcontroller based interface will necessitate programming of the microcontroller and a separate dedicated software package. While this has the potential to provide a faster control system sampling frequency, it adds the complexity of learning both the software and the device.

1.5 Dissertation Overview

- Chapter 2 – Literature Review

This chapter begins by answering the question what is a stroke. It is then broken into two distinct sections. The first takes a brief look at the use of PC game based Haptic and assistive devices used in the area of stroke patient rehabilitation. The second section focuses specifically on the use of driving simulators in stroke patient rehabilitation. Due to the protection of intellectual copyright and competition little specific information is available on the hardware of the simulators themselves.

Regardless the information found has been presented to provide additional context to the overall project.

- Chapter 3 – Conceptual Designs

This chapter takes a broad view of the initial stages of the projects and examines any possible solutions. The conceptual design process is documented here showing the progression of ideas, initial testing and research into different types of actuators, sensors and interface electronics.

- Chapter 4 – Detail Design of Mechanical Components & Selection of Electronics

Chapter 4 looks at the final components selected, the decisions and reasoning behind them and their design and implementation into a final system. Construction of the system is also covered in this chapter.

- Chapter 5 – Software Development

Divided into two sections microcontroller software and PC software, each part looks at the software requirements, implementation, and where necessary some specific problems encountered and their solutions.

- Chapter 6 – Testing and Results

This chapter documents methods and results used to verify the initially sensor readings and basic device operation. Additionally it details the processes used to prove the usefulness of the device and its data logging and scoring capabilities.

Chapter 7 – Conclusion and Further Study

This chapter outlines the scope and specificity of further work that can be conducted in the areas of software, electronics, driving assessment and development towards a commercial product.

Chapter 2 Literature Review

2.1 Introduction

The use haptic devices and virtually in stroke patient rehabilitation is still very much in its infancy. After providing a simple definition of stroke, a brief look is taken at the traditional methods of stroke rehabilitation. This chapter then focuses on the use of haptics devices and virtual reality environments in the context stroke patient rehabilitation

2.2 Stroke – A simple Definition

A stroke occurs when the blood flow to the brain is interrupted. The type of stroke Brain Foundation(2009) can be classified by the type of interruption of the blood flow, the first being an Ischaemic Stroke which is caused by a blood clot, the second a Haemorrhagic Stroke, caused by cerebral haemorrhage(burst blood vessel). Both types of stroke cause damage to the brain tissue resulting in a number of dead brain cells. The number and location of brain cells affected will determine the type and extent of the affects of the stroke on the patient.

The affects of stroke range from weakness, paralysis, loss of perception (touch or sight), depression, tiredness, incontinence, inability to read, write or speak, and cognitive impairment (the inability to think, reason or problem solve.) Hemiparesis, paralysis of only one side of the body, is common among stroke sufferers with 75% left with this type of disability.(Johnson et al 2003, vol.21 pp13)

Stroke is a serious concern in Australia being the largest neurological cause of adult disability. Out of 100 stroke patients, 30 will die in the first year mostly in the first 3 months. Of the 70 survivors around 35 will be free of disabling impairments or completely recovered. The remaining 35 retain a permanent disability after 1 year with 10 of those requiring permanent care in a nursing home or other facility. <www.brainaustralia.org.au>

2.3 Current Rehabilitation techniques

Rehabilitation helps stroke survivors relearn skills that where lost when part of the brain is damaged (National Stroke Foundation 2009). Rehabilitation experts agree that focused repetitive exercises, such as those utilised when learning a new skill like playing an instrument or sport, is the most important aspect in any rehabilitation program to ensure retention of the newly learned skill

The first 24 – 48 hours following stroke is a critical time, and rehabilitation is best started within this time frame.(National Stroke Foundation 2009) Rehabilitation begins with movement exercises that fall into either the passive or active category (from a patient's perspective). Where patients have little or no movement of a limb, passive range of motion exercises are undertaken where movement of the limb is actively assisted by a nurse or therapist. Alternately the patient undertakes simple active exercises with no assistance. Early exercises focus on range of movement and change of position such as rolling over or sitting up in bed and from lying down to sitting on a chair. Exercise progresses through standing, walking, and more difficult tasks like going to the toilet or bathing.

A range of disabilities can occur as a result of stroke however this project focuses mainly on those that result from some level of paralysis causing a loss of limb strength and motor control, in particular our interest is in that of the upper limbs and body. For this type of disability, post hospital rehabilitation is commonly undertaken by physical therapists and, occupational and recreational therapists.

While both physical and occupational therapists focus on motor and sensory impairments, physical therapists are more concerned with assessing strength, endurance, range of motion and sensory deficits. From this assessment, a program is developed with a focus on repetitive exercise and use of the impaired limb to promote brain plasticity. That is the brains ability to learn and adapt.

Complementary to the physical therapist, the occupational and recreational therapist focuses on motor and sensory impairments from a day to day task perspective. Where a physical therapist promotes individual limb exercises, the occupational therapist focuses on tasks such as dressing, making a meal, or cleaning the house. Additionally the occupational therapist is able to provide a level of driver retraining, where appropriate, including on road practice and assessment.

Frequently, due to the loss of movement or control over a muscle group a patient will need to learn a new technique or process of accomplishing a complex task. In such circumstances the therapist aims to have the patient break the task down into smaller simpler tasks, practicing those first. Accomplishing the complex task then becomes a matter of combining a series of simpler tasks already learned or mastered by the patient. While this type of rehabilitation is valuable to patient in becoming more self sufficient, there is some danger that learned non-use of an impaired limb will develop.

The short comings of traditional rehabilitation techniques include the number of therapist hours required for patient rehabilitation and therefore the number of patients that can be cared for by a particular therapist at one time and patient boredom and de-motivation stemming from uninteresting repetitive exercises of which it can be difficult to observe small, but sometimes significant improvements.

2.4 Computer based Haptic and assistive devices used in the area of stroke patient rehabilitation

Development Project D3: Targeting T-WREX to Improve Functional Outcomes of Upper Extremity Therapy
and "If I can't do it once, why do it a hundred times?": Connecting volition to movement success in a virtual environment motivates people to exercise arm after stroke.

The aim of the T-WREX project is the development of a therapeutic device for stroke patients with significant loss in strength and control of the arm and hand. The device should be usable in both rehabilitation clinics and in the home. Specifically, the device was aimed at compensating for the weight of the patients' arm due to gravity in an effort to provide the user with an exercise device without the need to overcome the weight of the impaired arm. To maintain device simplicity, in keeping with the goal of in home use, a non-robotic solution was sort, that is the device is passive only and does not provide any active assistance rather it compensates for the effect of gravity and allows the user to undertake exercises that were previously not possible due to their lack of strength and therefore inability to support the weight of their own arm. The other key components of the system included a grip sensor for detecting even the slightest grip and hand function, a virtual reality game environment designed to emulate and provide exercises found in normal day to day activities and, software capable of tracking and logging patient movement, providing real feedback about the patient's ability and progress.

Figure 2.1 – T-WREX Device

source <http://www.hocoma.ch/en/> viewed 5 May 2009

The design of the T-WREX device is based upon the WREX (Willington Robotic exoskeleton) consisting of 4 linkages, for freedom of movement and, a varying number of rubber bands to counterbalance the weight of the device and the arm. A number of modifications were made to the design, the result being T-WREX. An increase in size and strength of the device brought the device to a size more suitable for adults. The addition of sensors for the arm, and a highly sensitive grip sensor for the hand increased the ability of the device to monitor patient movement. On the software side the system includes a number of games representing real life tasks in a virtual reality environment with additional software for data logging and performance monitoring.

A study was undertaken to assess the systems effectiveness, subjective value of its various components and patient preference over traditional rehabilitation methods. The study included a control group of 12, using the T-WREX system, and a test group of 13. Each group undertook a 2 month training program. While the control group performed traditional table top type exercises the test group used the T-WREX device and virtual environment. At the end of the study each group was given the opportunity to try the other training technique. Performance and improvement in patient ability were made using the Fugl Meyer assessment with a comparison of results before and after training. The Fugl-Meyer Assessment (FMA) is a stroke-specific, performance-based impairment index. It is designed to assess motor functioning, balance, sensation and joint functioning in hemiplegic post-stroke patients. (*Fugl-Meyer Assessment of Sensorimotor Recovery After Stroke (FMA)*, StrokEngine Assess). Subjective and preferential assessment of the device was made via a post training questionnaire and subsequent telephone survey. Specifically, participants were asked to compare which system they preferred, which aspects of the T-WREX system they found most valuable and beneficial, and what type of improvements to the T-WREX system would they find most valuable.

While both the test group and the control groups showed improvement in quality and amount of use of their impaired limb, the vast majority of the participants preferred T-WREX over the traditional table top technique. Participants described T-WREX as less boring, and that they would be more likely to complete home exercises. Specifically participants in the test group found T-WREX more interesting, more challenging, and having more success in moving their impaired limb coupled with the added benefit of the performance feedback available from the software. Participants also indicated a high value for the addition of a device that allowed more hand and wrist movement, followed by robotic assistance. Of least value was the addition of more games with a strong preference for games that emulated day to day activities like grocery shopping, cleaning the stove or driving as opposed to arcade style computer games.

The potential of the T-Wrex device and software when developed into an at home exercise and training device for stroke patient rehabilitation represents a real step forward in current rehabilitation methods. It represents a significant reduction in the number of therapist hours required per hours of beneficial rehabilitation training undertaken by the patient. This is especially so as the simulation software holds the interest and motivation of the patient independently of the therapist interaction.

Figure 2.2 T-WREX Game Example

source <http://www.hocoma.ch/en/> viewed 5 May 2009

Motivating Rehabilitation By Distorting Reality

The aim of this study was to evaluate the affects of error augmentation on patient movement towards a specified target where error was regarded as the distance from the ideal. Previous research has shown that "improvements occurred when the training forces tended to magnify errors but not when the training forces reduced the errors or were not present at all. (Paton et al 2006) More specifically they investigated how stroke patients adapt when the error in their movements is magnified.

A number of experiments were conducted beginning with a baseline assessment were no error augmentation was present. Following a number of training exercises with error augmentation, a final assessment was conducted with the training forces removed. The baseline and final assessments would provide a direct comparison and evaluation of patient improvement.

The system is comprised of two key sub systems, a haptic robotic force feed back system named The Virtual Reality and Robotic Optical Operations Machine(VROOM) and a virtual reality display system known as the Personal Augmented Reality Immersive System(PARIS).

The VROOM system consists of a number of robotic end effectors that attach to one of two PHANToM robots, see figure 2.3, that provide a workspace measuring 900 x 900 x 300 mm with a maximum continuos force of 3 Newtons with transient peaks of 22 N . Different robotic arms allow the system to be reconfigured to suit the various scales of force and motion. The system incorporates a magnetic tracking system to trace position and orientation of limb segments and head position.

Figure 2.3 PHANToM Haptic Sensor Robotic Arm

source < http://www.societyofrobots.com/robot_arm_tutorial.shtml>

To avoid a slow or lagging display system, that has the potential to cause motion sickness or catastrophic instabilities when controlling haptic systems, PARIS utilises a half silvered mirror that allows the user to see their own limb and the real world. Stereographic images of virtual objects are projected onto the screen via a cinema quality digital projector. The effect is that of transposing the objects over the real, producing a display some 5 feet wide at a resolution of 1280 x 1024 with a view angle of 110^{o}. The user wears a special set of LCD shutter glasses that facilitate synchronisation of the image.

Experimentation required the user to move their hand from it's current position in a straight line to an indicated target. Following the collection of baseline results, various methods of error augmentation were applied for the next phase. Error augmentation techniques included amplifying the visual error(offset) or by providing an error amplifying force. The final phase was conducted under the same conditions as the baseline results to evaluate any retained improvement in the participants' ability.

Both of these methods of error augmentation resulted in an improvement in the participants' ability to follow a set trajectory, with the improvement lasting around 15 minutes after the error augmentation had been turned off. This result was significantly longer than the improvement experienced by unimpaired subjects. The study concludes that "the judicious manipulation of error (through forces and or visual distortions) can lead lasting desired changes by including adaptation". Further the study found that the results were unaffected by background conversation or music without the intense concentration required of conventional learning mechanisms.

While the VRROOM system possess the ability to provide the user with complex 3D movements and tasks common to everyday life, the system represents a significant level complexity itself. While potentially suitable for research facilities or large rehabilitation clinics, installation en mass seems unlikely the system is clearly unsuitable for in home use. The system is however, a valuable tool in evaluating rehabilitation training methods and techniques, as demonstrated in their research, that may then be applied to simpler and less expensive devices.

2.5 Driving Simulators and Stroke Rehabilitation

Design and Evaluation of Drivers SEAT: A car steering simulation environment for upper limb stroke therapy

Stroke patients suffering hemiparesis frequently use their unimpaired limb to overcome the limited use of their impaired limb. This is particularly so in an activity such as steering a car where typically both arms are used. Drivers SEAT (Simulation environment for Arm Therapy" is a unique force feedback car steering simulator able to provide both assistance and resistance as required. The device is constructed in such a manner as to actively discourage the use of the unimpaired arm while encouraging the use of the impaired arm.

The system uses a specially designed split steering wheel equipped with uni-axial load cells enabling the system to determine which arm is providing the resistance or movement force. Position measurements are taken via a 4096 count optical encoder wheel while a resistive or assistive torque is applied via an electronic motor. The system as described is connected to computer controlled hardware that in turn is connected to a PC running driving simulator software.

To facilitate patient focus on the steering task an appropriate speed is held constant for the duration of the simulation therefore braking or accelerating inputs are not required. Three steering modes are available, passive movement (PM), active steering (AS), and normal steering(NS). In the NS mode light self centering torque is applied to the steering wheel, as one would expect to feel in a normal driving mode. This mode is used as a general exercise mode for the patient while giving an opportunity to assess how the patient distributes input forces from both their impaired, and unimpaired arm. PM mode is used for patients who have no movement in their impaired limb whatsoever. In this mode the feedback mechanism compensates for the weight of the impaired limb while the unimpaired limb undertakes the steering task.

The AS mode is designed to actively encourage the use of the impaired limb while discouraging use of the unimpaired limb. Since the system, via the split steering wheel and load cells, can differentiate between forces applied by each limb, a force applied by the unimpaired limb makes the steering more difficult. Conversely a force applied by the impaired limb causes the feedback mechanism to ease or reduce the effort required to steer.

A small sample group of four subjects was performed, monitoring the subjects ability to track(stay on the required course) under the NS and AS modes. Due to the small size of the group conclusions were difficult to reach. There was some indication that the AS mode encouraged usage and level of effort from the impaired limb. The system was able, however, to collect data relating to impaired/unimpaired usage strategy while undertaking the steering task.

This type of device shows promise but with a need for more research with larger number of participants necessary to validate the methods and techniques employed. The custom load cell equipped steering wheel is highly effective at differentiating between forces exerted by the impaired or unimpaired limb but at the expense of device cost and complexity.

Effect of Simulator Training on Driving After Stroke: A Randomised Trial

This study aimed to evaluate and compare the benefits of post stroke driver training in either a simulator environment or while undertaking more traditional training. Eighty-three patients participated in the study and were placed in either a control group that under took a series of driving related cognitive tasks while the experimental group undertook training in a driving simulator.

Both groups received an intensive training program spanning 5 weeks at 15 hours per week. An official fit to drive assessment was undertaken before and after the training program.

The simulator was a full bodied car using the STISIM drive system. Images were projected onto a screen approximately 2.3 m by 1.7m with a view angle of 45^{o}.

While adaptive aids such as a right side indicator stick and left-sided accelerator could be attached if needed, the simulator was not specifically designed for stroke patients.

Rather the system was developed specifically for driver training purposes with the ability to create various scenarios that could be focused on developing particular driving skills. The experimental group undertook a 13.5km scenario lasting around 25 minutes.

Post training evaluation revealed an improvement in both the experimental and control group, however on a fit/unfit to drive basis a significant benefit was found for the experimental group. The research suggests that post stroke driver training is useful part of the rehabilitation process with a preference for simulator based training.

As with the other devices and studies this programme shows promise for simulator based training. The device is clearly unsuitable for home use and would be far more suited to large research or rehabilitation facilities.

P-Drive: Assessment of Driving Performance After Stroke

While the focus of this study is the Performance Analysis of Driving Ability(P-Drive), a non computer based driving skill assessment tool, the assessment environment is a simulator and the subjects are stroke patients. The greatest advantage of the simulator environment is the ability to simulate dangerous or challenging situations that would either be unsafe or not encountered on the road.

P-drive contains 20 criteria that used to assess the quality of driving of the subject. The assessment however is performed not by the computer but by a person trained and experienced with the P-drive system.

The simulator is a half car, providing the driver with real car controls. Three large screens providing a view angle of 135^{o} are used to display the driving program. The software consisted of a test program with a choice of 70 traffic situations. A typical 'drive' would take 40-60 minutes depending on the level of competency and number of mistakes made by the participant.

Like the other studies mentioned the number of participants in this study was quite small at just 31. Results of the study showed that the P-Drive assessment tool was able to "separate the participants according to their different levels of driving ability".

While the P-Drive system and half car 3 screen simulator were shown to be a useful tool in the assessment of driving ability, the physical system is quite large and most likely beyond the budget of many rehabilitation systems. Likewise the P-drive system requires constant attention of the therapist or assessor in addition to the need for special training. A further probable disadvantage of the use of the system across a broad number of rehabilitation clinics and assessors is the relative subjectivity and interpretation of each assessor.

2.6 Conclusion

The literature review has shown that there are great benefits to be had from the use of haptics devices and virtual reality environments in the context of stroke patient rehabilitation. These types of devices are able to hold the patients interest and keep them motivated. Importantly the devices are able to provide data about patient progress. Unfortunately, with the exception of T-WREX, most of the devices are only suitable for research work, or use within a rehabilitation clinic. T-WREX is well on the way to being developed into a system suitable for use in the home.

Driving simulators have significant benefits for driving retraining over conventional methods that included cognitive therapy and potentially dangerous on road retraining. It is not suggested that a simulator replace on road training, but rather be used as a safer intermediate tool to provide assessment of the patients progress and ability before venturing out onto the open road. There is a need then for a force feedback steering wheel and driving simulator designed specifically for use within the context of stroke patient rehabilitation. This is especially so of devices suited for either supervised use in a rehabilitation clinic, or unsupervised use in the patients' home.

Chapter 3 Conceptual Designs

3.1 Introduction

This chapter details the development of the conceptual design and design requirements. A brief look is taken at the shortcomings of commercial game controllers that render them less than suited to this application. A broad view is taken of the components or blocks that make up the system and their relative interconnections to provide a framework for the design. Before considering each block in greater detail the required feedback torque is calculated. Each block is then considered determining its specific requirements, the various options available and the reasoning behind the choice of one option over the other.

3.2 Short Comings of Commercial Game Controllers

There are a number of force feedback steering wheel game controllers currently on the market. Most of these share a number of key limitations that make them somewhat less than suitable or desirable for rehabilitation. First and foremost is that of accessibility to the device. Assuming that the system will work under a Windows based PC environment then access to the outputs of the device and control of the feedback is strictly via Direct-Input, a subset of Microsoft's Direct-X. Programming driver software or working with Direct X is a highly specialised task and therefore well outside the skill set available for this project. This is especially so given that an entirely new and unfamiliar programming language will need to be learned from scratch to develop the game software.

While the devices themselves are suited to the game environment, they generally lack finesse and feel. This is primarily due to their low power input, around 18W. To produce sufficient torque to provide the feel and 'kick back' found in many games the devices use a high ratio gear box. Therefore the motor and gearbox is back driven when the user turns the steering wheel from lock to lock resulting in a slow and heavy feel. Typically the devices have a limit of 270^{o} of rotation lock to lock. While this may be suitable for the early stages of rehabilitation, situations such as u-turns, parking or negotiating a round-a-bout is not really possible.

From a sensor or output perspective, the devices are strictly limited to steering position (angle). While steering rate could be derived mathematically from the change in position a dedicated sensor gives a more accurate result without the need to successively read the position. Force or steering torque cannot be measured with these devices. While it may be possible to calculate the torque, if data could be accessed about the feedback being applied, the accuracy of such a calculation would be questionable and require a significant amount of work to calibrate and validate the result. This is especially so given the high ratio of the gearbox.

3.3 Concept System

The system is comprised of number interactive components or blocks that link the simulation environment, computer game, to the physical device. A personal computer, PC, provides a platform for the simulation and effectively forms one end of the system. At the opposite end is the steering wheel to which some power source, such as a motor or actuator must be connected to provide feedback torque to the user. Additionally the steering wheel must be equipped with at least an angular position sensor to provide information to the PC about the user inputs. It may also be beneficial to provide other sensor feedback such as velocity or torque that may be used for control of the device or to provide data about the users' strength or ability. Some type of interface circuitry is then required to connect the sensors, process the signals and send them to the PC. The PC or the interface circuitry will also determine how much feedback torque should be applied. Since the control signal from the circuitry is likely to be very small, a form of power amplification will be needed before the signal can be applied to the feedback device. A block diagram of the concept system is shown in figure 3.1 giving a broad view of the blocks or modules that make up the system and how they are connected to one another.

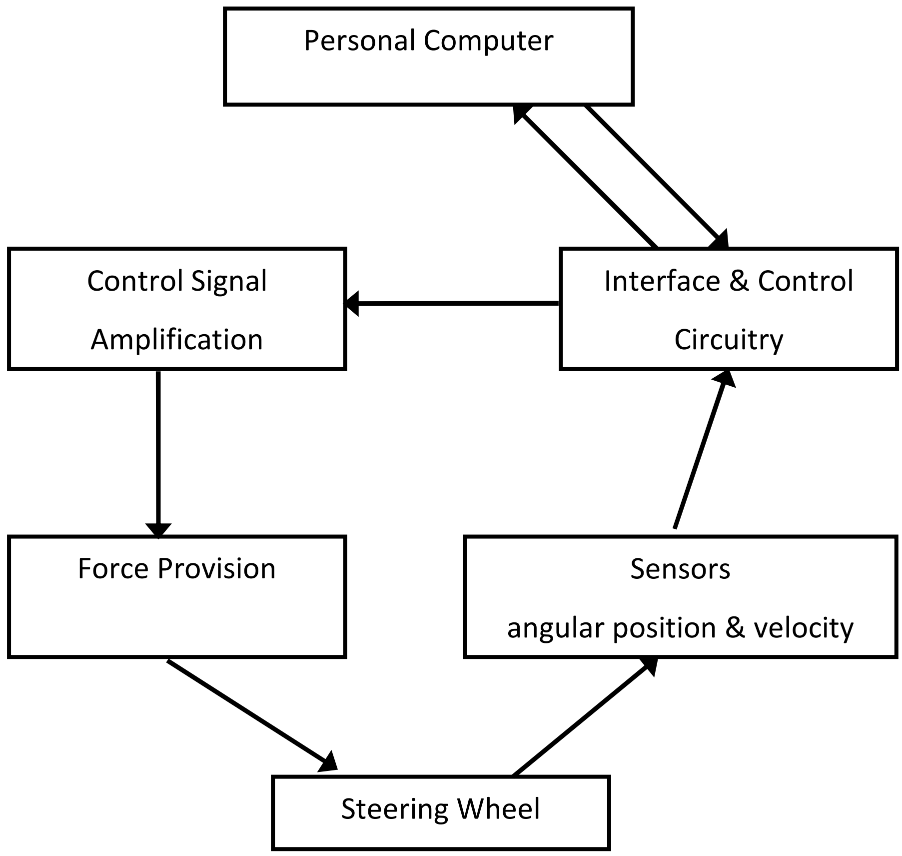

Figure 3.1 System Concept Diagram

3.4 Determination and Calculation of Required Ttorque

The first stage of the conceptual design process was focused on choosing the type of mechanism that would provide the resistive or assistive torque to the steering wheel. Since data was not readily available on the size of the input forces necessary to steer a vehicle and experimental approach was taken in an attempt to find a maximum amount of torque required to steer a car. Torque sensors are expensive and fitting them to the steering wheel of a car could become a time consuming process in itself. Likewise the approach of fitting a torque wrench to the steering wheel seemed inherently dangerous, and still would require a custom designed and built device to attach it to the steering wheel.

Therefore a very pragmatic approach was taken utilising a spring balance tied to rim of the steering wheel. The measured tangential force multiplied by the steering wheel radius would give torque. Measurements were taken from two different sources, firstly an older style Thrustmaster T2 steering-wheel game controller, figure 3.2, and secondly a 2004 model Hyundai Getz with power-steering.

Figure 3.2 Thrustmaster T2 Game Controller

The Thrustmaster game controller is one of the older style controllers that provides an average feel, but does not possess any active force feedback, the centering force is provided by a piece of elastic. The diameter of the steering wheel was measured at 270mm. A peak force of 2kg was measured by the spring balance.

$$F = mg$$
$$F = 2 \times 9.81 = 19.62N$$
$$T = Fr$$
$$T = 19.62 \times \frac{.270}{2} = 2.65Nm$$

Since it would be difficult and potentially dangerous to attempt to measure the steering wheel torque while the car was moving, a maximum or worst case could be found with the vehicle stationary, engine running and foot on the brake. With this approach, any steering torque required while the vehicle was moving would be significantly less than the torque measured.

The diameter of the steering wheel was measured at 370mm and a peak force of 3kg was required to turn the wheel.

$$F = 3 \times 9.81 = 29.43N$$
$$T = 29.43 \times \frac{.370}{2} = 5.4Nm$$

Based on these measurements the peak design torque was set at 5Nm.

3.5 Design Requirements

The design requirements for the device were broken down into the following categories, feel, upgradeability and modularity, data measurement, mode of operation, and cost.

Feel

The device should provide a more realistic feel than the commercially available game controllers. Specifically the steering wheel should generally feel lighter and smoother. It should also show a marked improvement in feel over passive devices that utilize a spring or elastic to provide the centering force.

Upgradeability and Modularity

With any project of this nature significant amounts of time and expense can be used in the development of a single component for the system in an effort to provide the best possible solution. Given the relatively short timeframe of the project (6-9 months) it was decided that a more modular approach should be taken. That is rather than designing a component to the exact specification required, wherever possible a pre-built off the shelf components should be used.

By designing the device with upgradeability in mind, the device can be built simply and cost effectively at a lower specification and upgraded as time and money allow. This approach also provides buffer that may be necessary to overcome unforeseen problems or obstacles.

Data measurement

Ideally the device would be able to provide measurements or data for steering angle, steering rate and steering torque. While steering angle is used as the primary input for the simulation, both steering rate and steering torque are able to provide useful information about the users' controllability and strength.

Mode of Operation

Research into the methods used for rehabilitation is still in its infancy. Methods include enhancing or magnifying the error in movement, limiting or decreasing the error, or complete control where the user is able to get a feel for the correct movement. To provide the best usability the device should be designed and constructed in such a way as to be flexible in its mode of operation and be able to provide active or passive, assistance and resistance or any varying combination.

Cost

Cost is an important aspect of any project. While the budget for the prototype is less than \$250(AUS), cost of the final product also has to be kept in perspective. One of the aims of the design is to produce a device that is small enough and inexpensive enough to allow the device to be located in the home as well as in rehabilitation clinics.

3.6 Design concepts – Force Feedback Mechanisms

The mechanism for providing feedback forces to the steering wheel is central to the design of the device. Therefore design of the feedback mechanism was given precedence over the other aspects of the project such as sensors and interface electronics. Each mechanism was considered for cost, controllability, size, force, and complexity.

Single Electric Motor

A single DC motor connected to the steering wheel shaft via some form of low ratio "transmission" should be able to provide sufficient torque. To achieve this, the motor will need to run at stall for most of the time, therefore a motor with relatively high stall torque and relatively low stall current would be needed. A wide range of electric motors are available either new, second hand or as surplus stock so the cost of a suitable motor is expected to be low. The motor can be controlled with a PWM (pulse width modulation) signal to vary the output torque so controllability of a single motor is very good. While a single motor represents little in the way of size and complexity, a H-Bridge motor control circuit is required to provide bi-directional control. This type of circuit represents a significant level of complexity and can be tricky to design without prior knowledge and experience. By contrast, unidirectional control can be achieved with a circuit as simple as single logic left MOSFET transistor and protection diode.

Dual Electric Motor

A dual motor design was considered in an effort to reduce the complexity of the drive circuit. Controllability is easily on par with a single motor design, and may even have a slight advantage in that the motors could be driven "against" one another if the need arose. Where this type of design gains in simplicity of drive circuitry it more than loses out in the extra space and cost required for two of everything. Additionally the control algorithm could easily become more complex than a single motor solution.

Stepper Motor

Stepper motors have great controllability by virtue of their 'stepping nature'. With advanced control techniques micro-stepping is possible making them highly suited to precision position control devices. While the size and controllability of stepper motors makes them attractive solution, they are significantly more expensive when compared to a standard DC motor. Likewise stepper motors tend to have very poor holding torque when compared to standard DC motors.

Hydraulic /Pneumatic

Both hydraulics and pneumatics are more than capable of providing the required torque. While actuators and motors are sufficiently compact and there is a wide variety to choose from they require an additional power source in terms of a compressor or pump which quickly make the solution large and unsuitable for use in the home. Hydraulics invariably leak and require maintenance in the form of oil and filter changes rendering them even less suitable. Add to this the difficulties involved with precisely controlling the force and position of the actuators and it quickly becomes apparent that a hydraulic or pneumatic solution is somewhat unsuitable.

Constant Velocity Flywheel with Variable Slip Clutch

The use of a flywheel and clutch represents a novel solution and is worth some discussion. A flywheel rotated at constant velocity by an electric motor could store enough rotational energy to provide the required feedback torque. Since the flywheel provides and energy reserve the size of the electric motor can be reduced. Power or torque can be transferred to the steering wheel shaft via a servo operated clutch mechanism. By varying the amount of slip, via the servo, the amount of torque applied to the shaft can be varied. By controlling the rate of change of slip different effects could be simulated for example a sharp pulse could be used to simulate a bump. To provide feedback forces in both directions however would require two flywheel clutch assemblies spinning in opposite directions.

Clutch size and wear represent significant problems for this type of solution. The amount of torque transferred changes as the clutch wears in, so too the amount of servo travel must be continually adjusted over the life of the clutch. Clutch life is also a significant obstacle with the clutch needing to slip most of the time, then glazing of the flywheel surface will also become a problem. Additionally the clutch will need to be custom designed, in order to keep the clutch diameter to a minium a multiple clutch plate solution would probably be need. While it may be possible to overcome these problems this solution is significantly less favourable in light of the other solutions already discussed.

Choice of Primary feedback mechanism

A DC motor based solution has shown to be most feasible and is best able to meet the design requirements. This type of solution represents very good controllability, is clean, requires little maintenance and is compact making it ideal for in-home or in-clinic installation. It is feasible to by a surplus stock motor for the prototype and the cost of motors purchased in wholesale quantities also makes the solution attractive. While single motor design requires a more complex drive circuit the cost and complexity savings over a dual motor design make the single motor design easily the most attractive.

Transmission Selection

A number of transmission options were considered. Direct drive to the shaft it not feasible unless and expensive or custom designed motor is used. To ensure lightness of feel it is desirable to minimise the gear ratio as much as possible. Therefore a gear ratio much greater than 10:1 is considered undesirable.

Some testing was conducted with a steel cable drive. A 10mm brass pulley was attached to the motor shaft and a small steel cable was wound around the pulley twice before being tensioned. Even at very high cable tensions slipping was still apparent and the approach considered unsuitable.

V-belts are a widely used power transmission mechanism. V-belt applications primarily rely on angle of wrap and belt tension to determine their maximum transmission torque. Belt slippage is highly undesirable in this application as is the high bearing loads that are likely to result from the necessary belt tension. Therefore a more positive drive transmission was sought.

A gear drive is well suited to this type of application, providing a no slip drive and an almost endless range of ratios. A toothed belt and pulley shares similar benefits, but was considered more suitable from a perspective of smoothness of feel and therefore was chosen in favour of a gear drive. Time and cost permitting a side by side test of the two drive mechanisms would provide a more definitive appraisal of the effect each mechanism has on the smoothness of feel.

3.7 Design Concepts – Sensors

A number of sensors are required to provide data back to the game environment, rehabilitation therapist and the devices' own control mechanism.

A suitable position sensor will be easy to read and connect to the electronics interface. The sensor should have a resolution of around $\pm 0.5^{o}$ and provide at least 300^{o} of rotation. While a greater rotation than this is desirable in the early stages of development this is sufficient. Three different position sensors were considered an analogue potentiometer, an optical encoder wheel and a gray encoder.

Potentiometers provide a very simple method of reading the steering angle needing only a power supply and connection to and ADC (Analogue-to-digital) converter. As an analogue device their resolution is really only limited by the resolution of ADC that reads them. They are available in single turn, 10 turn or continuous. Most single turn pots have a useable angle of less than 300^{o} and a 10 turn pot is excessive and is likely to result in a lower resolution. Continuous pots on the other hand often exceed 300o without loss of resolution.

Optical encoders such as the one shown in figure 3.3, are used extensively in industry for position sensing applications. Position is read by counting the pulses or gaps in a encoder wheel by means of a photo interrupter. Care must be taken when reading the pulses so that no pulse is missed while not unnecessarily bogging down the interface circuitry. While a single optical sensor is sufficient for providing the change in position two sensors are required for direction. Then there still must be some strategy for

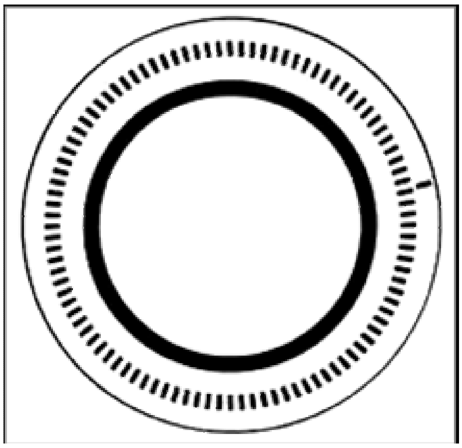

Figure 3.3 Optical Encoder Wheel

Encoder wheel image http://www.suc-tech.com/technology/e5.gif

finding absolute position if the starting point is not necessarily constant.

Gray Encoders, such as the one shown in figure 3.4 also called an absolute position encoder, use a number of stripes around a disc that is encoded so that when the array of optical sensors the binary output of the array is the absolute position of the wheel. Resolution of these devices is limited by the size of the wheel and the bit resolution of

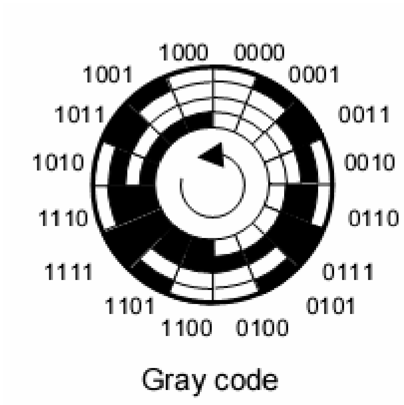

Figure 3.4 Gray-Code Rotary Encoder

source <www.scienceprog.com/using-gray-code-for-rotary-?encoders/>

the sensor array. Gray encoders also tend to be relatively expensive in comparison to optical encoder wheels and potentiometers.

Measuring the steering rate (velocity) should provide better control of the system as opposed to deriving the velocity from a change in position. Measuring the velocity directly gives an immediate response. This measurement may also be useful to a rehabilitation therapist, to gain greater insight into how well the patient is able to control the steering wheel. A magnet and hall-effect sensor could be used to determine the velocity but will still require a degree of processing. By contrast a small DC-motor can be used as a tachometer to directly measure the velocity. Some filtering and amplification of the signal may still be necessary, but this will depend on the choice and availability of motors for use as a tachometer.

Provision of a force or torque sensor is considered an option at this stage of development and is an example of the need to design the system to be “upgradeable”. Measurement of the steering torque would provide information to a rehabilitation therapist about the patients’ strength. Rotating torque sensors are available commercially but are well outside the budget of this project. Since output torque is related to motor current a shunt resistor (in the order of 50mΩ) could be used to measure the current drawn by the motor. Interfacing the circuit would require amplification of the voltage drop across the resistor which is likely to me in the order of millivolts. Some filtering may also be necessary to remove any back-emf noise although it may be possible to locate the sensor between the power supply and motor control board and simply deduct the current drawn by the control board in an idle state.

3.8 Design Concepts – PC interface Electronics

The sensors and associated drive electronics need to be connected to a PC to provide data logging and for the simulation environment. The interface should be bi-directional, that is it should be able to either directly control the motor send control modification signals to a micro controller. As a minium the interface should have sufficient inputs and outputs for up to 5 ADC channels used initially for steering position and steering rate, but with room for expansion to accommodate sensors for steering torque, accelerator and brake. The interface should also have a number of digital inputs for other functions such as gear change or emergency stop. The interface

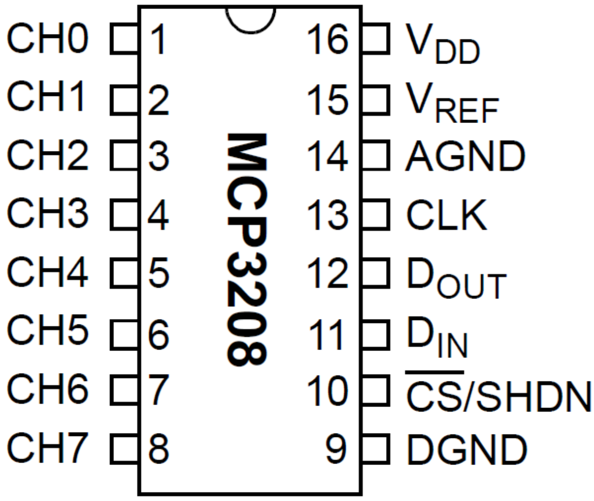

Figure 3.8 MCP3208 8 Channel 12 Bit A/D Converter Pinout Diagram

will also need a PWM output for motor control.

Direct Control via PC's Parallel Port

An ADC chip such as MicroChip's MCP3208 12 bit 8 channel ADC could be connected to the PC's parallel port. Four pins or control lines from the parallel port are needed to control the chip and are connected to the Din, Dout, CLK and DGND pins. Communication with the chip is via a bit banging method, where a piece of software would need to be written to send control data bit at a time to the chip for selection of the ADC channel and input type. The conversion result is then banged back out 1 bit at a time. A further 2 output lines from the parallel port would be needed to directly turn on or turn off one pair of MOSFET's (Metal Oxide Field Effect Transistor) on the motor driver control board.

While it is possible to create the interface as described above the vast majority of new PC's do not come equipped with parallel ports. Additionally a significant amount of software code is necessary to control the interface and could impact the performance of the simulation.

PicAxe

The PicAxe brand of micro-controllers are based on a selection of microcontrollers from MicroChip. The chips are preloaded with bootstrap code that allows them to be reprogrammed using nothing more than a serial cable. Software for the microcontrollers is written in a free but proprietary PIC Basic.

The devices are very easy to learn to program even for those without a programming background or prior knowledge of microcontrollers. The devices are available as a chip only, pre-built development board or complete starter kit. Prices range from $5 for the 8 pin chip only to around $120 for the 40pin starters kit making them quite a cost effective solution. While some powerful devices are available the degree of flexibility is lost by using the Basic code. Therefore full access to the features of the chips is not available, particularly in the area of timers and interrupts.

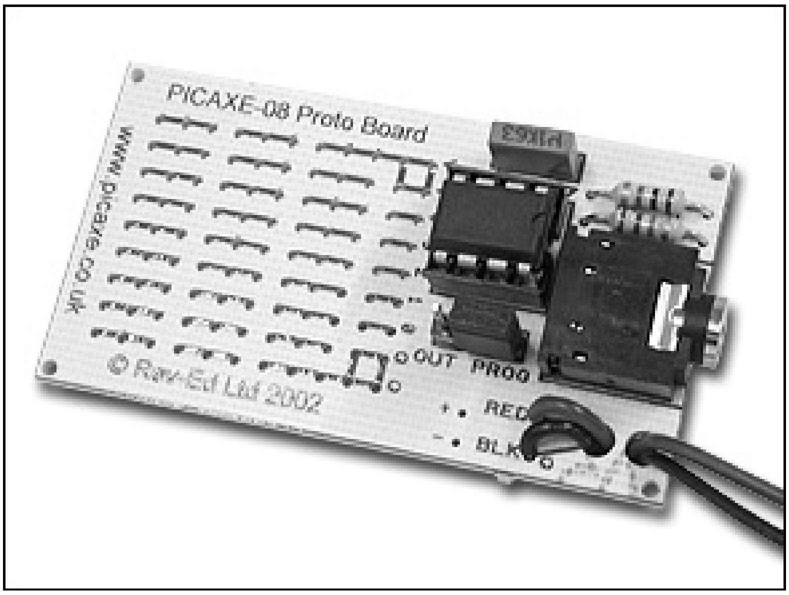

Figure 3. 6 PICAXE-08 Proto Typing Board

source <http://www.microzed.com.au>

Velleman USB Interface kit

Velleman produce two USB interface boards based on PIC micro-controllers an entry level board, the VM110 and an extended board, the VM140. Both boards are produced as either a prebuilt module or kit form. Once the board is connected to a PC's USB port then various board functions are accessed by '*including*' the supplied DLL (Dynamic Linked Library) module in any one the of .NET languages available in Microsofts Visual studio package. Alternately software can be developed in any other 32-bit Windows application development tool that supports calls to DLL's.

The greatest advantage of this type of solution is that the boards come pre-programmed that is no microcontroller code, firmware, needs to be written. Therefore only one programming language is used for the project greatly simplifying the development process. A comparison of the features and performance of the two boards is shown in the table 3.1.

Table 3.1 Comparison of Interface Board Features

Feature	VM110 USB Interface Board	VM140 Extended USB Interface Board
ADC Resolution	8 bit	10 bit
ADC Channels	2	8
PWM Channels/Resolution	1 – 10 bit	1 – 10bit
Digital Inputs	5	8
Digital Outputs	8	8
Analogue Outputs	2 – 8bit	8 – 8bit
Typ Command Conversion Time	20ms	4ms

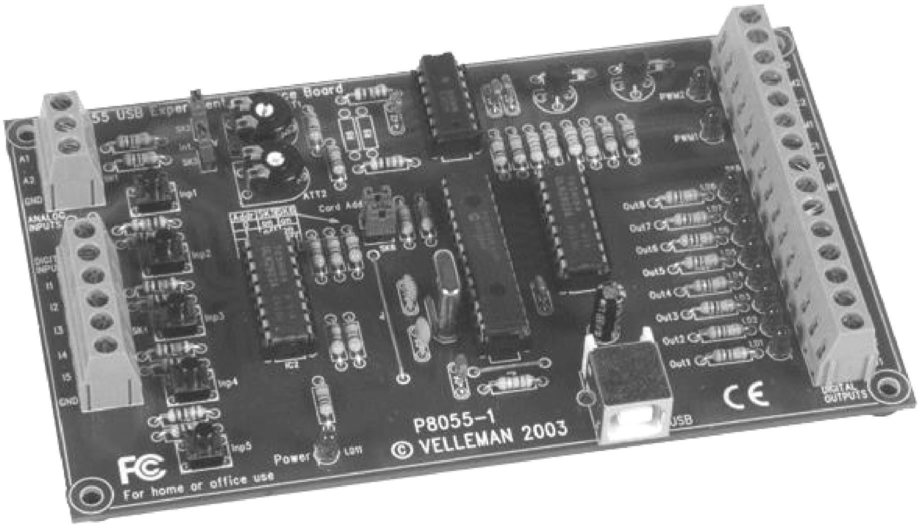

Figure 3.7 Velleman VM110USB Interface Module

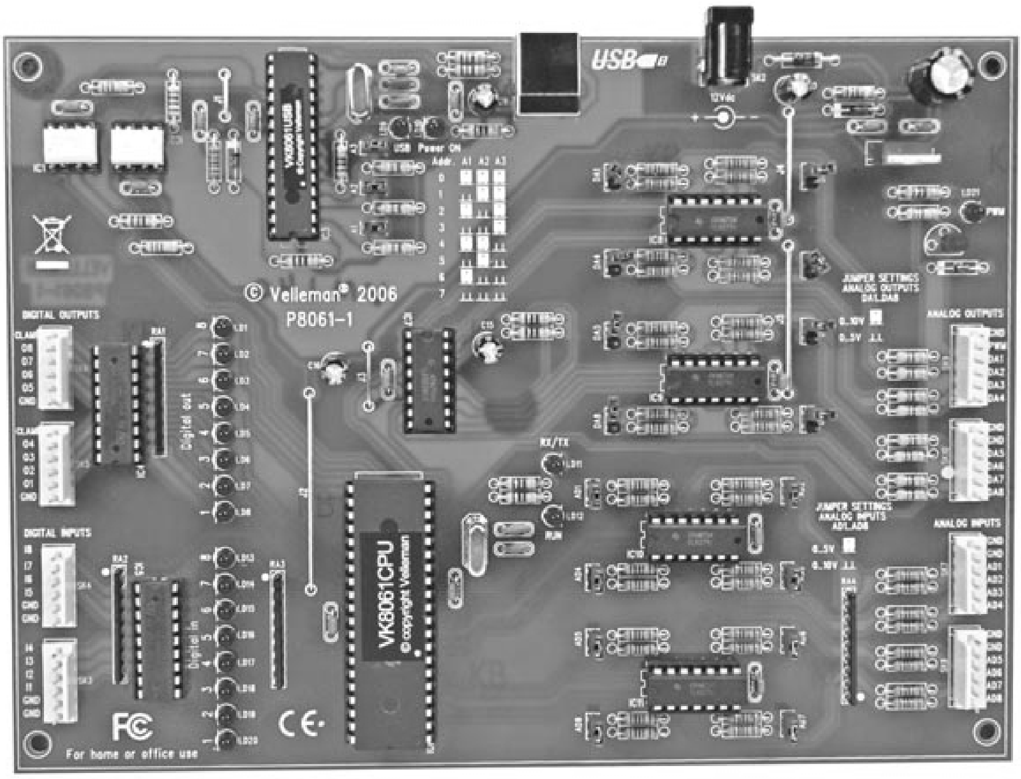

Figure 3.8 Velleman VM140 Extended USB Interface Module

While the project could be started with the VM110, the conversion time is marginal and it lacks upgradeability with only 2 ADC channels. The ADC resolution falls short of the resolution required as well. By contrast the VM140 is highly suited to a project of this nature and was initially chosen as the interface solution for this project. Unfortunately the pre-assembled module could only be purchased from overseas and at a cost exceeding the whole budget of the project.

A kit version of the board, K-8066, was found locally but still at a cost of over $200AUS. With over 350 solder-points on the board and no guarantee of a working board on completion it was felt that a more cost effective solution could be found.

PIC Microcontroller Based Solution

A wide range of PIC microcontrollers is available from Microchip, many of which would be suitable for this project. In keeping with a modular approach however, it was decided that a PIC based development board should be evaluated. The decision was further motivated by the availability of technical support from within the faculty and access to the Oshonsoft PIC Basic development environment. Oshonsoft Basic does not suffer from the same limitations as the PICAXE platform, allowing the user full access to all the features of the chosen micro-controller. In some situations this may require writing small sections of code in Assembly language, or directly accessing the chips registers but can be accomplished without great difficulty.

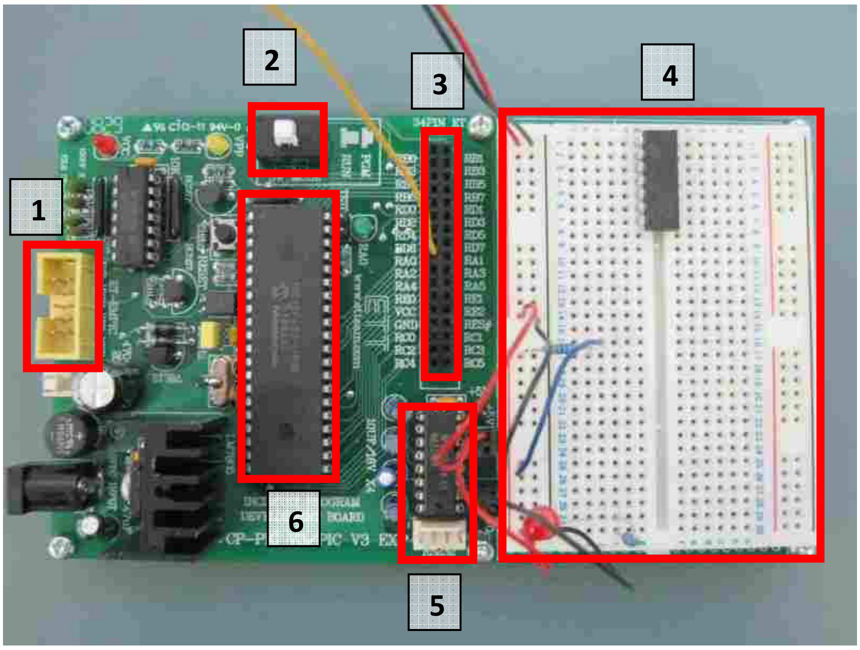

Figure 3.9 PIC 18F458 Micro-controller Development Board

1– In circuit serial programming socket	2- Program/Run Selection Switch
3- IDC Connecter Socket – Chip I/O Pins	4- Prototyping Bread Board
5– Max232 Chip & RS232 Serial Port	6- PIC 18F458 Microcontroller Chip

A PIC18F458 based development board was found from Futurlec at a cost of less than $50AUS. The board has 33 I/O points, including 8-10bit resolution ADC channels and 4-10bit PWM channels. Additional features included a prototyping breadboard, 10MHZ clock speed, RS232 communications with on-board MAX-232 chip, and in circuit programming capabilities direct from the parallel port with programming software and cable supplied therefore the expense of a separate chip programmer is avoided.

The board represents an excellent level of performance and upgradeability for a relatively low cost without sacrificing accessibility. This type of solution also presented some flexibility in application of the control algorithm not previously considered. The

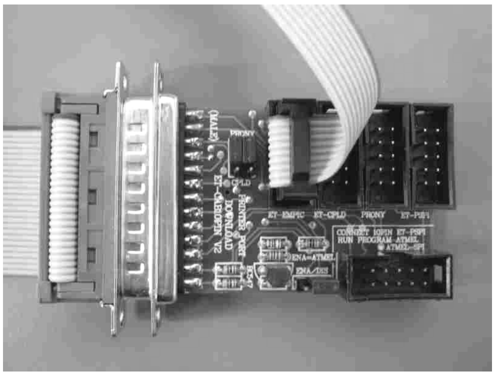

Figure 3.10 In Circuit Serial Programming Board

board could be used simply as an I/O device with the control algorithm being coded as part of the simulation software. While this approach provides a much simpler and flexible approach it does so at the cost of speed with data being collected by the interface board, sent to the PC, a control signal calculated and then sent to back to interface board. Alternately the micro-controller collects the data, calculates and applies the control signal, and then sends the data back to the PC for the simulation environment and for data logging. This approach ensures that the control signal is available sooner but is not without its own limitations. The control algorithm must be written without the use of negative numbers and floating point numbers. That is the code is restricted to the use of unsigned integers only, meaning the algorithm code will be more complex than that written in a higher level language such as VB.NET or C#.NET.

3.9 Motor Driver Circuit

Choice of motor drive circuitry is based on three criteria: control must be bi-directional, proportional and have sufficient power handling capabilities for the application. To aid in the selection of a suitably sized controller some initial assumptions were made with regard to the motor and power supply.

To constrain the cost of a suitable power supply the voltage of the supply should be restricted to 12V and current restricted to between 10A and 15A. At these limits a bench power supply or sealed lead-acid battery would be suitable. It is also necessary to restrict the maximum current draw of the motor since at stall all the power of the motor is dissipated as heat were $P_o = I^2R$. Since the current is squared large currents quickly become very large amounts of power dissipated as heat.

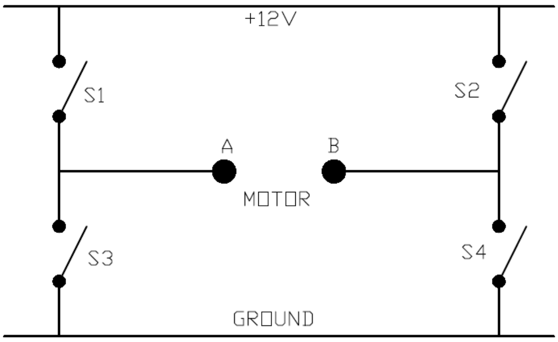

Figure 3.11 Simplified H-Bridge

Bi-directional control of a DC-motor requires the use of a circuit know as a H-bridge, a simplified schematic is shown in figure 3.11 . Reversing the direction of rotation of the motor is achieved by reversing the direction of the current flow. Consider the case where switches 1 and 4 are closed while switches 2 and 3 remain open. Since terminal A of the motor is then connected to the positive voltage rail while terminal B of the motor is connected to ground let us assume that this causes the motor to turn clockwise. If switches 1 and 4 are then left open while switches 2 and 3 are closed then we have the reverse situation where terminal B is connect to the positive supply and terminal A to ground which will cause the motor to turn counter-clockwise. In practice the switches are replaced with power MOS-FET transistors that are capable of handling the large currents necessary for controlling the motor.

Proportional control of a DC motor can be achieved through the use pulse-width modulation. Each pair of FET's in the bridge are switched on and off at a given frequency. By varying the on and off times, as shown in figure 3.1, the effective voltage, V_{avg}, seen by the motor varies resulting in proportional control of the motor.

The ratio of the pulse width to the frequency is known as the duty cycle and is usually expressed as a percentage. So if 25% drive is required the FETS are turned on for 25% of the period and off for 75% of the period and so on as the duty cycle is increased.

In keeping with the modular approach a pre-built or kit motor driver module is preferred over custom designed and constructed H-Bridge.

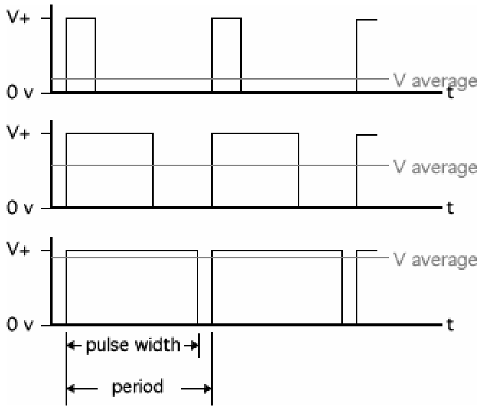

Figure 3.12 Pulse Width Modulation

http://www.societyofrobots.com/schematics_h-bridgedes.shtml

3.10 Conclusion

An initial system concept was developed, outlining the various modules that make up the system before discussing the suitability and shortcomings of the shelf game controllers. These short comings include a limited range of rotation and a poor or overly heavy feel. Additionally the controllers are difficult to access from a software perspective requiring a high level expertise in the area to understand device drivers and Direct-X programming.

The design requirements of the device have been defined, in order to make the device suitable for use in a rehabilitation environment. More specifically the device needs to be able to provide a feedback torque of up to 5Nm while remaining relatively smooth. The device also must have the ability to collect data to assist in rehabilitation, and to that end the device must be small enough and cost effective enough for use in rehabilitation clinics or in the home.

A number of methods of providing the feedback were examined, including the use of hydraulics, pneumatics, slipping clutches and electric motors. An electric motor was chosen as the most feasible solution for this application due to their controllability, relative compactness and cost. Having determined an electric motor should be used the selection of a h-bridge based motor driver board follows logically as the best method of providing bi-directional control.

It was also determined that, in terms of range of angle, precision and ease of reading that a continuous potentiometer would be the best sensor for reading the steering wheel angle. A small DC-motor was then selected as a velocity sensor to directly read the steering rate rather than rely on derived velocity signals from devices such as hall-effect sensors or other types of position sensors.

While the first choice in interface electronics was the Velleman USB Extended interface board, the cost, availability and risks associated with the construction of the board meant it was an unviable solution. An alternative was found in the selection of PIC18F458 development board that provided a good level of performance and flexibility while remaining cost effective.

With the exception of the choice of interface circuitry, selection of specific components has been avoided in the conceptual design phase. After careful consideration of the previous discussion the following '*modules*' were chosen for development into a prototype.

Feedback Source	Single Permanent Magnet DC Motor 0.5Nm Stall Torque
Power Transmission	Toothed Drive Belt
Position Sensor	Continuous Potentiometer
Velocity Sensor	Small DC Motor as a tachometer
Torque Sensor (optional)	Shunt Resistor
Interface Electronics	PIC 18F458 Prototyping Development Board
Drive Circuitry	Off the shelf H-Bridge, kit or module 12V 20A

Chapter 4 - Final Prototype Design

4.1 Introduction

The prototype design process was approached by first selecting the components that would be most difficult or of which there was a limited selection of sizes. Taking this approach meant the DC motor would be selected first, followed by drive pulleys and belts, potentiometer, and tacho-motor. With these major components selected design of the main shaft and other mounting blocks, hubs and adapters could be done. As the designed components would be manufactured by the USQ workshop this design work would take precedent over the electronics design work.

4.2 Selection of a DC Motor

Since a limit of 10A stall current is desired, the torque available at 10A was calculated for each motor. The required gear ratio for a steering-wheel torque of 5Nm could then be calculated bearing in mind that maximum desired gear ration of 10:1 has also been set to ensure a minimum loss in feel.

Data for these specific motor characteristics was not available for every motor considered. The following variables and equations were used to calculate these characteristics.

Rated Power	$P_o(Watts) = P_{in} - P_h$
Rated Current	$i_R(Amps)$
Rated Voltage	$V(volts)$
Rated Speed	$n_R(RPM)$
Rated Torque	$T_R(Nm) = \frac{60P_o}{2\pi n_R}$
Stall Torque	$T_{stall}(Nm)$
Stall Current	$i_{stall}(Amps)$
Torque Constant	$k_t(Nm/A) = \frac{T}{i}$
Torque@ 10A	$T_{10}(Nm) = i_{max}k_t$

Gear Ratio $r = \frac{T_{required}}{T_{10}}$

Electrical Power In $P_i(Watts)$

Power dissipated as heat $P_h(Watts) = i^2 R_a$

Armature Resistance $R_a(Ohms)$

A number of motors were evaluated for suitability by examining their respective stall torques and currents and calculating the gear ratio necessary to produce the desired torque.

Table 4.1 - DC Motor Comparison

	YM – 2776 Jaycar	**Mabuchi RS – 755 VC**	***JX MY-68**
			
Stall Torque	6.0 Kg/cm (0.589 Nm)	0.422 Nm	-
Stall Current	57 A	22 A	-
Torque Constant K_t	0.010 Nm/A	0.019Nm/A	0.057Nm/A
Torque at 10A	0.103 Nm	0.190 Nm	0.570 Nm
Gear Ratio Required	48.5:1	26.3:1	8.7 : 1
Cost	$24.95	N/A	$29.95
Rated Power	-	-	100W
Rated Current	-	-	6A
Rated Voltage	12V	18V	24V
Rated Speed	-	-	2750 Rpm
Rated Torque	-	-	0.347Nm(calculated)

*note that this was a surplus motor from Oatley Electronics, and has since become unavailable.

The MY-68 was chosen as the best motor and was the only motor found for a reasonable cost that could meet the torque requirement and current limit without exceeding the maximum gear ratio of 10:1

4.3 Transmission Design

A range of timing belts and pulleys is available from Small Parts and Bearings at a reasonable cost. Assuming a maximum pulley radius of 75mm, to limit the overall size of the device, then an estimate of working belt tension can be found.

$$F_B = \frac{T_{shaft}}{r_{pulley}} = \frac{5Nm}{0.075} = 66.7N$$

Belt pre-tension was estimated by examining the 'slack' side of the belt. Under full load this side of the belt still needs to be in tension. The tension in the tight side of the belt will be the sum of the pre-tension and the working tension while the slack side will be the pretension less the working tension. Since it is desirable to have a reasonable amount of tension in the slack side of the belt the pre-tension was estimated to be twice the working tension. This would result in a slack side tension equal to the working tension and a tight side tension equal to 3 times the working tension or around 200N. Unfortunately little information is available from this supplier with regard to working tension and maximum tensile stress, only belt braking force is given. For a belt of 10mm width constructed of polyurethane with steel cords a braking force of 1190N is given. Given a working tension of 200N a belt of this type should produce a reasonable working life for the prototype.

A cross section of the belt tooth geometry is shown in figure 4.4. The belts were available in three metric pitch sizes, 2.5mm, 5mm and 10mm. At a pitch of 2.5 it was felt that the tooth would be too small last a reasonable length of time, while a pitch of 10 would have a tooth length(T) of 3.25 and may lack the flexibility required to bend around the small radius required on the motor drive pulley to achieve the desired gear ratio. Therefore a pitch of 5mm was chosen.

Timing pulleys of this pitch were available from 10 teeth through to 84 teeth. By taking a pulley from each end a ratio 8.4:1 could be achieved, only slightly less than the 8.7:1 ratio calculated. Based on this achievable ratio the maximum expected torque at 10A is 4.8Nm or 96% of the peak design torque. This small deviation was acceptable and not expected to have an adverse affect on the performance of the device, therefore a 10 tooth motor drive pulley and 84 tooth main pulley were selected at a cost of $16.60 and $23.76 respectively.

An estimated spacing of 250mm between pulley centres was used to determine the timing belt length. A spacing greater than this starts to make the assembly too large while decreasing the spacing reduces the angle of wrap around the smaller pulley and therefore less engaged teeth which is undesirable. The angle of wrap and total belt length were found graphically as is shown in figure 4.5. Angle of wrap around the small pulley 360^{o}-207^{o} =153^{o} which should provide sufficient engagement of the belt and small pulley.

Product features, benefits and information

T Series Metric Timing Belts.
Pitch (P) - 5.000mm.
Tooth Length (T) - 1.40mm.
Tooth Height (H) - 1.20mm.
Belt Height (W) - 2.20mm - Corner Radii (r) - 0.40mm.
Breaking strength is not indicative of working strength.

All dimensions on this website are shown in mm unless otherwise indicated
Click on linked part numbers in the table below for more details

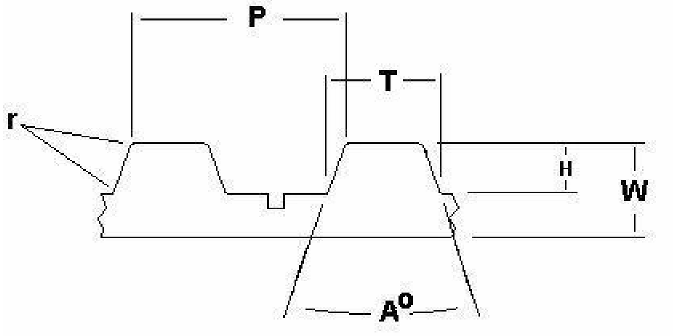

Figure 4.1 Timing Belt Dimensions

www.smallparts.com.au/store/partslist/beltstiming10000m

A timing belt of 150 teeth and 750mm in length was selected at a cost of $18.67. A belt of this length would also allow the use of a larger motor drive pulley, provided the tensioning mechanism is designed with sufficient travel.

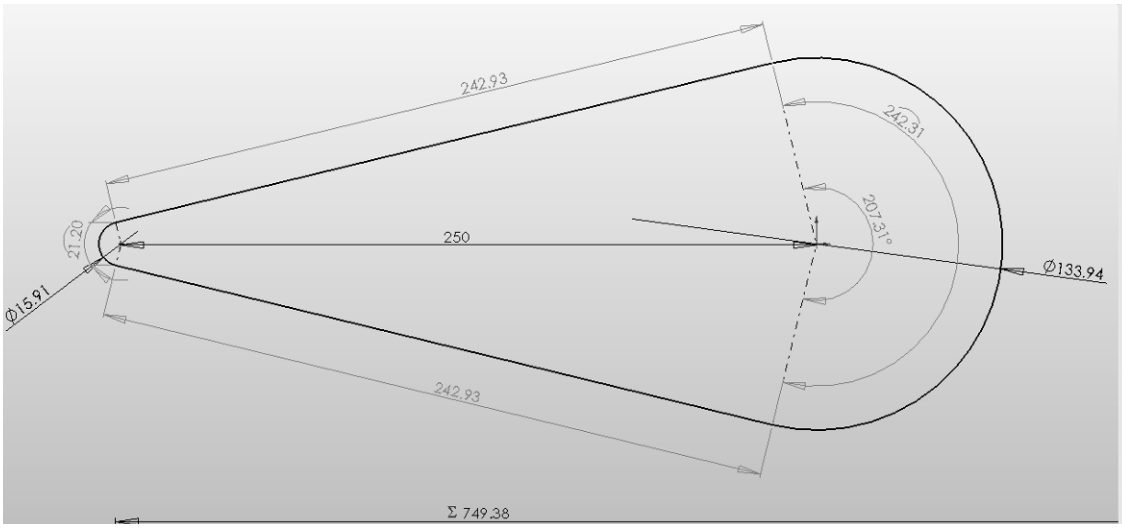

Figure 4.2 Belt Length and Angle of Wrap

4.4 Bearing Selection

Bearings present a lower friction solution and therefore less loss in feel of the device. Sealed bearings eliminate the need for the external lubrication that could easily become messy. Ball bearings also suitable for use for the light axial loadings present in this type of application. To keep the design of mechanical components simple the size of the bearings and shaft were chosen to match the bore diameter of the main pulley at 10mm. Width and external diameter of the bearings was chosen based on the most common size and therefore least expensive size available. A 3D model of the bearing is shown in figure 4.3.

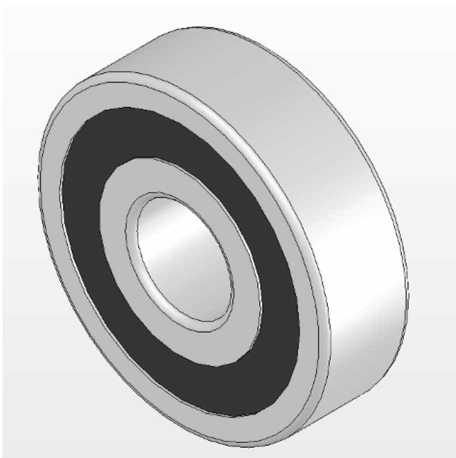

Figure 4.3 Sealed Bearing 10ID x 30OD X 9

4.5 Mechanical Design

A computer aided solid-modelling approach was used for the mechanical design. Key measurements were taken of all the purchased components where necessary. A pair of vernier callipers were used to ensure accuracy. Special note was taken of shaft sizes, position of mounting holes, screw threads, flanges etc so that accurate solid models could be created in Solidworks 2007. A 3D model of every component was created including every bolts set-screw, clip and washer. Taking this approach allowed all the components to be pre-assembled before a single component was manufactured. The interfaces and connection of all the components could then be checked for alignment and interference to ensure the device could be assembled and that the mechanism would function as designed.

Bearings are pressed into aluminium front and rear mounting blocks to support the main shaft. The blocks are thicker than is necessary due to availability issues with thinner material. Some re-design work of the front and rear mounting blocks was necessary to accommodate the use of the thicker material, in the form of deeper recesses and a stepped section on the rear block.

A shoulder at the front of the main shaft rests against the bearing in the front mounting block. A small collar fits on the shaft from the opposite side of the bearing and is fixed in place with a set screw to prevent axial movement of the shaft.
A circlip is used behind the rear bearing to prevent movement of the main shaft and more importantly prevent any axial loads being applied to the potentiometer..

The steering wheel hub is manufactured from aluminium bar and provides a means of mounting the steering wheel to the shaft while ensuring sufficient clearance between the steering wheel and the front mounting block. The steering wheel is attached to the hub by three bolts while the hub is secured to the shaft by a pair of set screws that are tightened down to a corresponding flat on the main shaft.

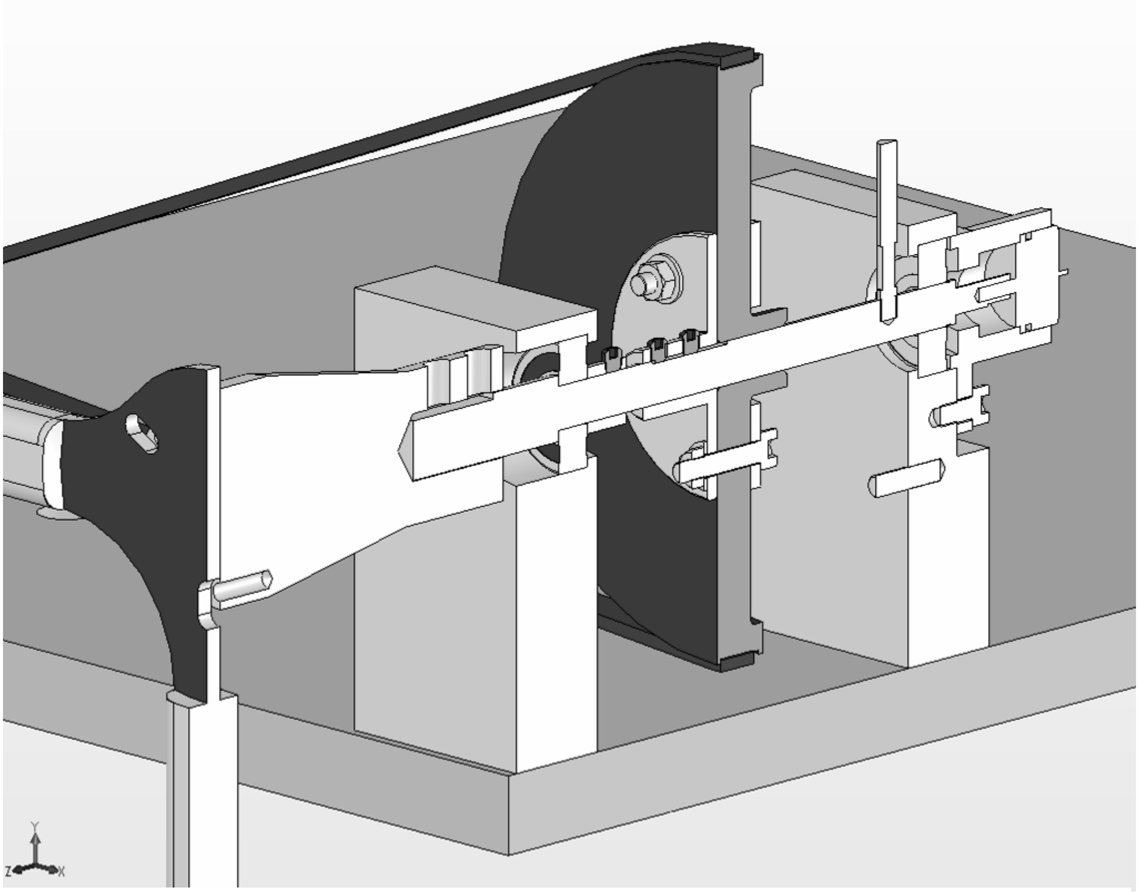

Figure 4.4 Sectioned View of the Main Assembly

Steering wheel rotation is limited by a dowel pressed into the rear mounting block and pin that screws into a thread tapped into the top of the main shaft. As the main shaft rotates the pin hits the dowel limiting rotation approximately 345°. The steering angle can be limited further if necessary by placing various sized discs over the dowel.

While the potentiometer mount is perhaps more complicated than is necessary, it was modified from an existing mounting bracket. To ensure concentric mounting of the potentiometer with the main shaft the mounting bracket has a shoulder that lightly presses into the bearing recess in the rear mounting block. The mounting bracket is fixed to the rear mounting block with a single screw while the potentiometer is held in place by three set screws located radially around the body of the potentiometer. The potentiometer shaft fits inside main shaft and is fixed with a small set screw.

Mounting the main pulley to the shaft was somewhat more difficult. While the hub is easily attached to the shaft via a pair of set screws and corresponding flat on the shaft, the pulley is made of plastic and is hollow in construction. To distribute the load as much as possible a pattern of 5 bolts is used in conjunction with a large flange on the hub. A circular retaining plate fits to the opposite side of the pulley to allow the bolts to be tightened without creating local stress concentrations around the bolts and the potential for cracks.

4.6 Tensioning mechanism and Motor Mounting

Belt tension adjustment can be accomplished in a number of ways including spring mounted idler pulleys or screw type adjusters. The design of this assembly, as with the

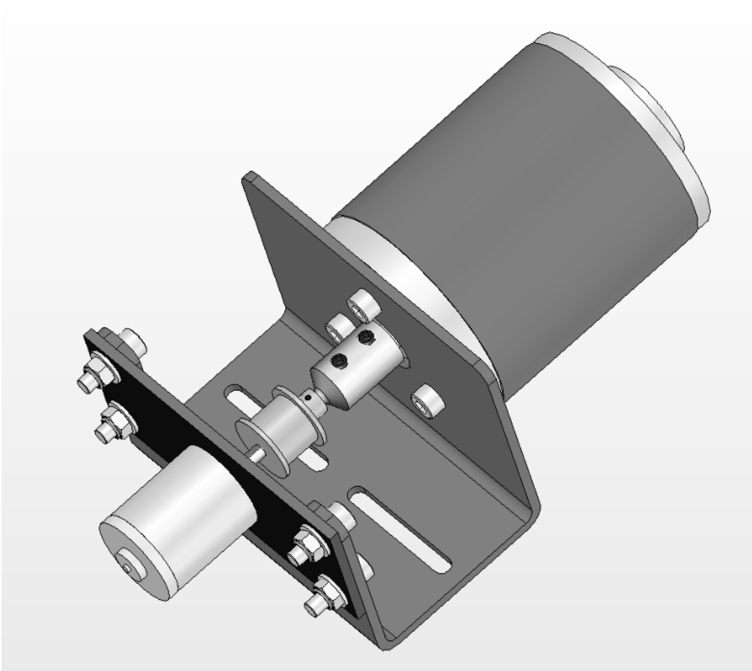

Figure 4.5 Motor – Tachometer Assembly

other components, was approached from the perspective of keeping the number of components to a minimum while keeping the design simple yet functional. By using slots to mount the assembly to the base rather than holes the entire motor assembly is able to slide providing a very quick and simple method of adjusting the belt tension. A common shaft provides a step down from the 8mm diameter motor shaft to the 4mm bore diameter of the drive pulley. Set screws are used to secure the adapter shaft to the motor and then the pulley to the adapter shaft. An important feature of the shaft is the slotted end that grips the tachometer shaft. Since the only torque transmitted through this connection is the resistance of the tachometer, a tension connection is more than adequate, simple to manufacture and quick to assemble. Since it is difficult to ensure concentric mounting of the main motor and the tachometer and given the very light loads on the tachometer a flexible rubber mount was designed from a flat section of rubber. The flexibility of the mount should more than cope with any shaft misalignment and ensure no unnecessary loads are applied to the motor or tachometer bearings. The flexible mount became a very important design feature, during initial testing it was discovered that the drive motor shaft was bent. The flexible mount worked very well in this case without providing any excess loadings on either the motor or the tachometer. The stretch provided by the toothed belt drive, was also sufficient to deal with the bent shaft.

4.7 Potentiometer Connection

A precision 10K continuous servo potentiometer, as shown in figure 4.6, was on hand and in good working condition. The specifications state rotation of 340^o $\pm 4^o$ and linearity of ±2.0%. Should it be necessary to use a different potentiometer in the future then only a new mount bracket and shaft adapter would need to be designed.

Connection of the potentiometer is very simple, requiring only 3 wires, with wiper connected directly to ADC port of the micro-controller as shown in figure 4.5

The analogue to digital converter has a resolution of 10bits or 1024 steps. Over a 5V range this gives a resolution of 4.88mV/step, 5V/1024 steps. Assuming that output signal from the potentiometer is 5V or a sampled value 1024 at 340^o then the expected resolution can be calculated at $340^o/1024 = 0.33^o$ / step.

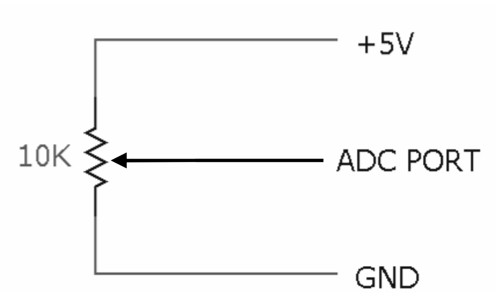

Figure 4.5

Potentiometer Connection Diagram

Figure 4.6 Vishay Spectrol

10K Potentiometer

4.8 Tacho-Motor Interface Circuit

A small 6 -12 volt DC motor, figure 4.7, was purchased to use as a tachometer. An initial test was conducted to determine the maximum output voltage of the motor when connected to main drive motor which was connected to 12V. The maximum output voltage measured was t ±1.2 Volts, a positive voltage for clockwise(CW) rotation and a negative voltage for counter-clockwise(CCW) rotation. Input to the micro-controllers ADC however requires a positive only signal in the range 0-5 Volts with a stopped voltage output of approximately mid rail.

An LM324op-amp (operational amplifier) was selected as the basis of the circuit due to its very low cost, availability and DIP package that is suitable for direct use on the breadboard. While the voltage output range of the LM324 is limited to its positive supply voltage -1.5V, rail-to-rail op-amps are generally only available in surface mount packages that necessitate the use of a custom PCB or surface mount to DIP adapter. Should the range and resolution of the output from the LM324 prove to be too limited then a rail-to-rail based option will be more closely investigated.

With a +5V supply the maximum output voltage of the op-amp will be 3.5V so the desired output for zero velocity will be half that or 1.75V. The interface circuit provides two function, offsetting the voltage to ensure the output is always positive and amplification of the signal to provide a larger range of voltages to the micro-controllers ADC port and therefore greater resolution. Table 4.2 summarises the input conditions and the desired output characteristics of the interface circuit.

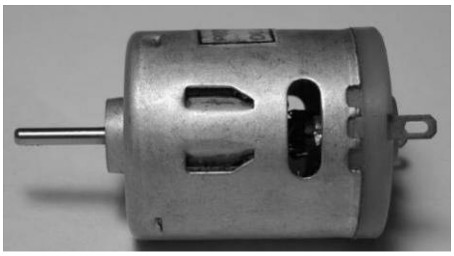

Figure 4.7 6-12V DC Motor

For use as a tachometer

Table 4.2 Tacho Interface Circuit Characteristics

Condition	Tacho- Output Voltage	Desired Amplifier Output
$Velocity_{max\ ccw}$	-1.2V	0V
Stopped	0V	+1.75V
$Velocity_{max\ cw}$	1.2V	+3.5V

A non-inverting amplifier configuration, as shown in figure 4.8, was used as simple an cost-effective method of increasing the output voltage.. The gain of a non-inverting amplifier is determined by the feedback resistors R3 and R4 and is given by the equation.

$$\frac{V_o}{V_{in}} = \left(1 + \frac{R_3}{R_4}\right)$$

Since a single power supply of +5V is to be used the input voltage from the tacho needs to be offset first. This is accomplished by building a voltage divider with resistors R1 and R2. The voltage at node 5 needs to be 1.2V so that a voltage of 0V is seen at the non-inverting input when the tacho is at maximum reverse velocity. The node voltage V_5 is calculated by the equation.

$$V_5 = V_{cc}\left(\frac{R_2}{R_1 + R_2}\right) = 5 \times \frac{15k}{62k} = 1.209V$$

The desired gain is found by examining the stopped condition, where the input to the op-amp is 1.2V and the desired output is 3.5V.

The ratio of the feedback resistors can then be found by re-arranging the equation.

$$R_3 = R_4\left(\frac{V_o}{V_{in}} - 1\right)$$

$$R_3 = R_4\left(\frac{1.75}{1.2} - 1\right)$$

$$R_3 = 0.46R_4$$

Choosing resistors from the E12 series R3 =27K and R4 =56K gives a working ratio of $R_3 = 0.46R_4$ and a gain of 1.48. While this gain is slightly larger than desired it will only have clipping or limiting effect on output corresponding to the maximum clockwise velocity which is expected to be outside the 'normal' working range of the device.

With a maximum sensor output of voltage of 3.5 volts the full resolution of the ADC requires a 0-5V signal. The maximum expected digital velocity reading will be 3.5/5*1024 = 716 counts with a stopped or zero velocity reading in the region of 716/2 = 358 counts.

4.9 Motor Driver Board

A 500W, 24V motor controller board was purchased from Oatley Electronics at a cost of $39, figure 4.9. The board has provision for 4 extra FETS that effective double the power handling capability of the board to 1KW. At the time of purchase the additional 4 FET's were available for under $10 and were also purchased. While the size of the board seems to be much larger than required, it does allow for a larger motor to be used in the future while ensuring that overheating of the board is does not become a problem. At $39 the board was significantly cheaper than anything else available at the time.

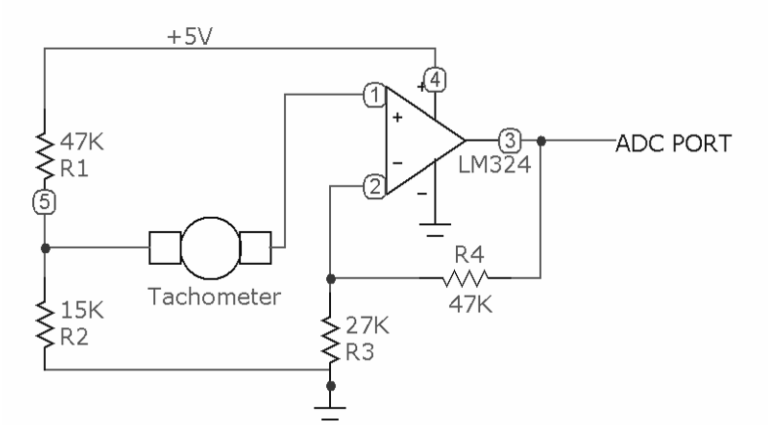

Figure 4.8 Tachometer Interface Circuit

The board accepts input via an analogue potentiometer or a 1-2ms pulse every 20ms. This type of pulse width signal is the same as that found in radio control planes or cars. The input signal to the motor driver board will be generated by the timers on the micro-controller and will be covered in greater detail in the next chapter.

The input signal interval of 20ms represents a potential issue in terms of quantisation error and controllability. With this limitation the control signal is only calculated and applied every 20ms, therefore if the change in position or velocity of the steering-wheel is large during the 20ms then an incorrect drive signal could be applied and may cause the system to oscillate or become unstable. An example of quantisation error is shown in figure 4.10

The blue line shows a sinusoidal signal sampled at 1ms intervals or a frequency of 1kHz, while the red line shows the same signal sampled at 20ms or 50Hz. The error between the two signals is largest at around 40ms, of course the effect here is exaggerated for illustrative purposes.

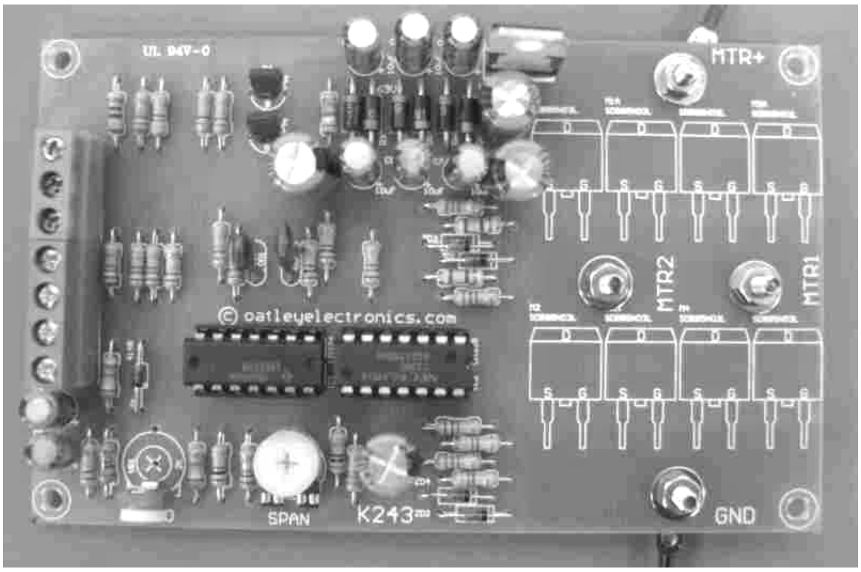

Figure 4.9 K243 – 1KW 24V Motor Controller Board

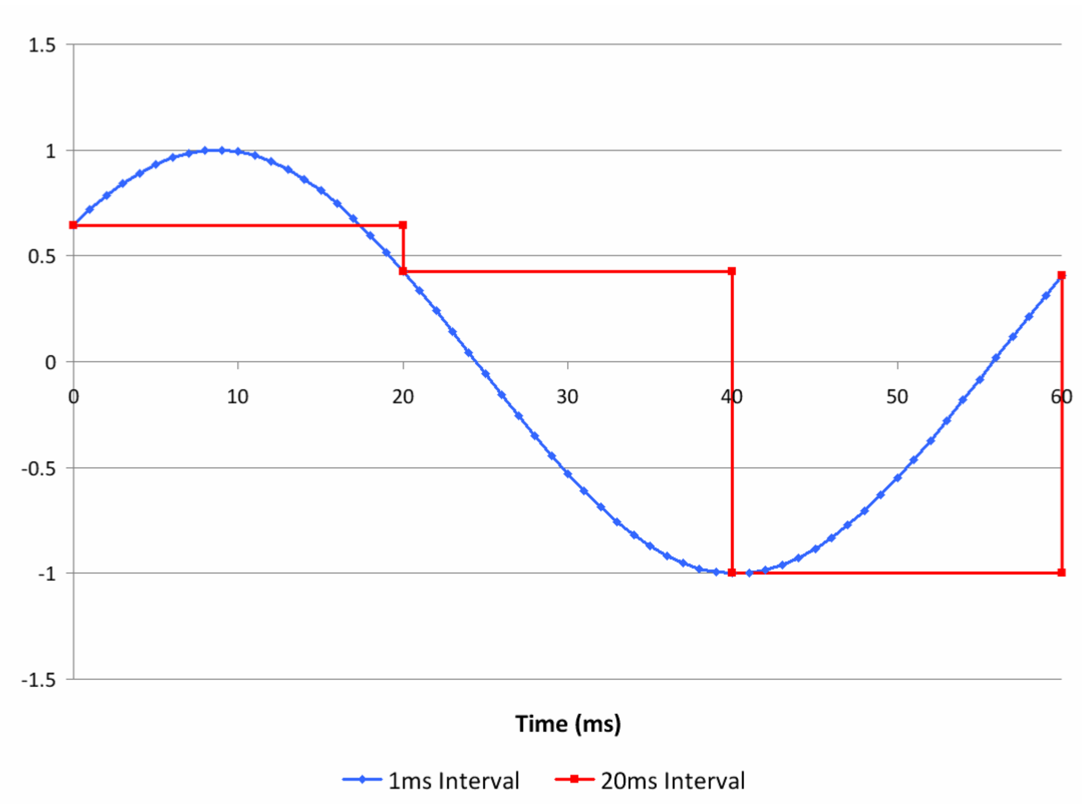

Figure 4.10 Example of Quantisation Error

Until the system is assembled and tested it is not known how significant an effect quantisation error will have on the accuracy of the data and controllability of the system.

Initially the error can be minimised by sampling the velocity and position, calculating a drive signal and applying it at the beginning of the 20ms interval as opposed to sampling the data at the beginning of the interval, and applying the calculated drive signal at the end of the interval.

Should the quantisation error or the drive signal frequency prove to be an issue then the motor driver board could be modified to provide more direct control of the FET switching and faster sampling and drive frequencies. Modifying the board however would require a detailed analysis of the circuit and most likely cutting of the PCB tracks. While more direct control is attractive the risk of permanently damaging the board or components was considered too high without first using the input available. Connection of the microcontroller to the motor driver board is very simple requiring only 2 connections, a signal and a ground.

4.10 Safety Circuit

A safety system, incorporating an e-stop (emergency stop) button as a minimum, is necessary to protect both the operator and the device. Given the gear ratio of 8.4:1 and a motor no load speed of approximately 2000RPM, if left unrestrained the steering wheel has the potential to spin unimpeded at 239RPM. If the operators fingers (or more likely thumbs) were on the inside of the steering-wheel they could experience nasty hit, that could result in a cut or severe bruising.

Additional risks of this occurring stem from the behaviour of the motor driver board. On initial power-on the FET's are not necessarily off causing the motor to kick momentarily. Also should the FET's fail to a short circuit then the full supply voltage would be applied to the motor causing it to spin at full speed. To avoid this, a relay was placed between the motor drive board and the drive motor, completely isolating the motor from any drive voltages until the relay is activated.

The safety circuit is designed and constructed around 2 logic chips and one transistor. A 74LS21 a dual 4-input positive-and gate provides the 7 logic inputs to the circuit, the eight input is used to chain the 2 and gates together. See figure 4.11 for the full schematicx. For this section of the circuit to output a logic-high all inputs must be above 2V, since all inputs are tied low with 1K resistors the pins cannot float high, they must be driven high by the input be that a sensor, micro-controller output or button. If any input drops to a logic low then the output also drops low causing the 'error led' to illuminate indicating that and error condition exists. As soon as the error condition is cleared the output goes high and the led turns off.

A row of header pins and jumpers allows any unused inputs to be tied high until needed. A momentary switch is hardwired to one of the input to act as an emergency stop button. Outputs from up to 6 other sources can be connected to the inputs and in the future could include an over speed sensor, over current sensor and enable from the micro-controller. Provision has been made on the board to fit a LM339 quad comparator that could be used to convert the analogue sensor signals to logic levels.

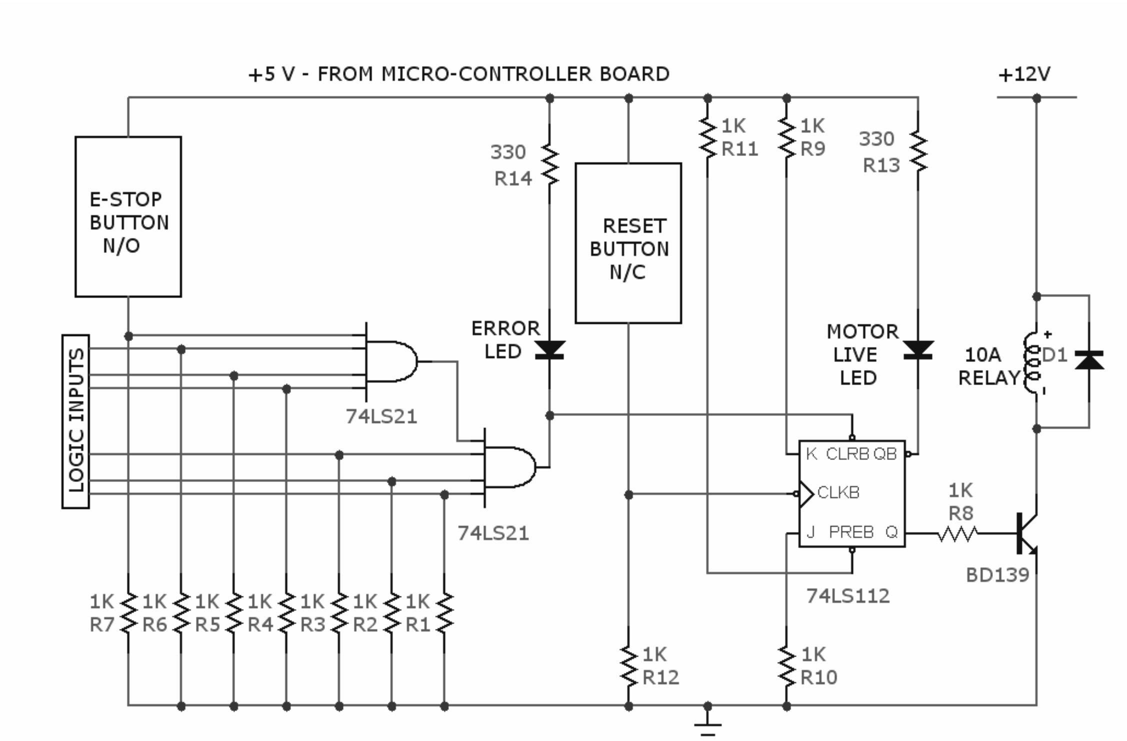

Figure 4.11 Safety Circuit Schematic

The second part of the safety circuit uses a 74LS112 Negative Edge Triggered J-K Flip-Flop to provide a safety latch. While the chip has 2 flip-flops only one is needed to provide the latching function. The latch needed to work in such a way so that once it is triggered by an error signal from the output of the and-gate it cannot be reset until the error is cleared. To achieve this, the flip-flop was configured in an unusual manner. If the Pre-set input is tied high and the CLR input drops low then regardless of the other inputs the Q output will be low and the relay will not be activated. For any change of state to occur the CLR input must first go high. A normally closed momentary switch is connected between the CLK input and the +5V rail while 1K pull down resistor is connected between the input and ground. In this configuration a high input will normally be seen at the CLK input, when the normally closed button is pressed the CLK input is pulled low by the resistor generating a negative or fall edge that in turn causes the flip-flop output to change state. An excerpt of the device function table is shown in table 4.3. It should be noted that only the two cases seen in normal operation are shown in the table.

Table 4.3 Negative Edge Triggered JK Flip-Flop Truth Table

INPUTS					OUTPUTS	
PRESET	CLR	CLK	J	K	Q	Q
H	L	X	X	X	L	H
H	H	↓	H	L	H	L

The final section of the safety circuit is a BD139 transistor that operates as a switch to engage the relay. When measured with a multimeter the relay coil was found to have a resistance of 180Ω, so when connected to a 12V supply it will draw around 67mA. To ensure the transistor operates in a saturated condition an appropriate base resistor is needed. Given the logic high level of the Q output is at least 2.7V and the gain of the BD139 NPN transistor is approximately 100 then the base current and therefore the base resistance can be calculated.

$$R_b = \frac{V_{OH} - 0.7}{I_c \times \frac{1}{\beta}} \quad R_b = \frac{2.7 - 0.7}{67 \times \frac{1}{100}} \quad R_b = 2985\Omega$$

The closest E12 series resistor is 2.7KΩ, and should ensure that the transistor turns completely on.

The operation of the overall circuit is summarised in table 4.4

Table 4.4 Safety Circuit Operation Table

Inputs			Outputs		
Logic Inputs	E-Stop Button	Reset Button	Error LED	Motor Enable LED	Motor Relay
Any input Low	X	X	ON	OFF	OFF
X	CLOSED	X	ON	OFF	OFF
All HIGH	OPEN	↓	OFF	ON	ON

It should be noted that the relay cannot be engaged unless the micro-controller board is turned on. On power-up the circuit defaults to a relay off condition ensuring no drive can be applied to motor until the rest button is pressed.

It is not possible for the micro-controller to reset the safety circuit in its current configuration. To reset the circuit the input must be driven low, since a normally closed switch and tie down resistor are used it is not possible for the micro-controller to drive the input low. The sole reason for the use of a normally closed switch was its colour, black, chosen to contrast the red e-stop button. This issue is easily corrected by substituting a normally open switch and using a pull up resistor instead of a tie down resistor.

The circuit was constructed on vero-board as shown in figure 4.12, while a simple control panel, figure 4.13, was made from aluminium. Several capacitors were added, both across the voltage supply and across the power inputs to the logic chips. This was necessary to reduced electrical noise that caused relay to self trigger to an off state

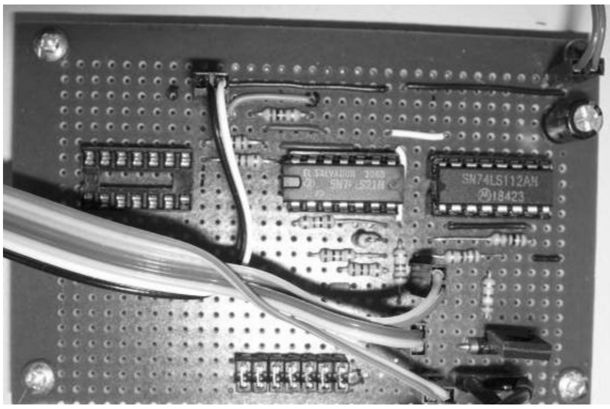

Figure 4.12 - Safety Circuit – Constructed on Vero-Board

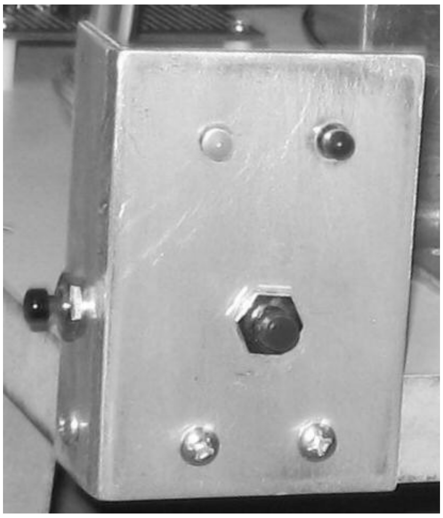

Figure 4.13 - Safety Circuit Control Panel

4.11 Conclusion

The off the shelf components have be chosen purchased including a 100W motor, timing pulleys, belts and bearings. Having created detailed 3D models of the purchased components the remaining mechanical components could be designed and assembled into a 3D assembly model, figure 4.14 before creating detail drawings of the components for manufacture. Appendix D shows the progression of the device from initial the 3D model, to the mechanical assembly and the completed device mounted with the micro-controller board, motor driver board, safety circuit and relay. The accuracy of the solid models can be clearly seen, the only exception being the steering wheel which was modelled as a concept only and the mounting holes matched to the real wheel.

Assembly of the mechanical system was very straight forward with most components

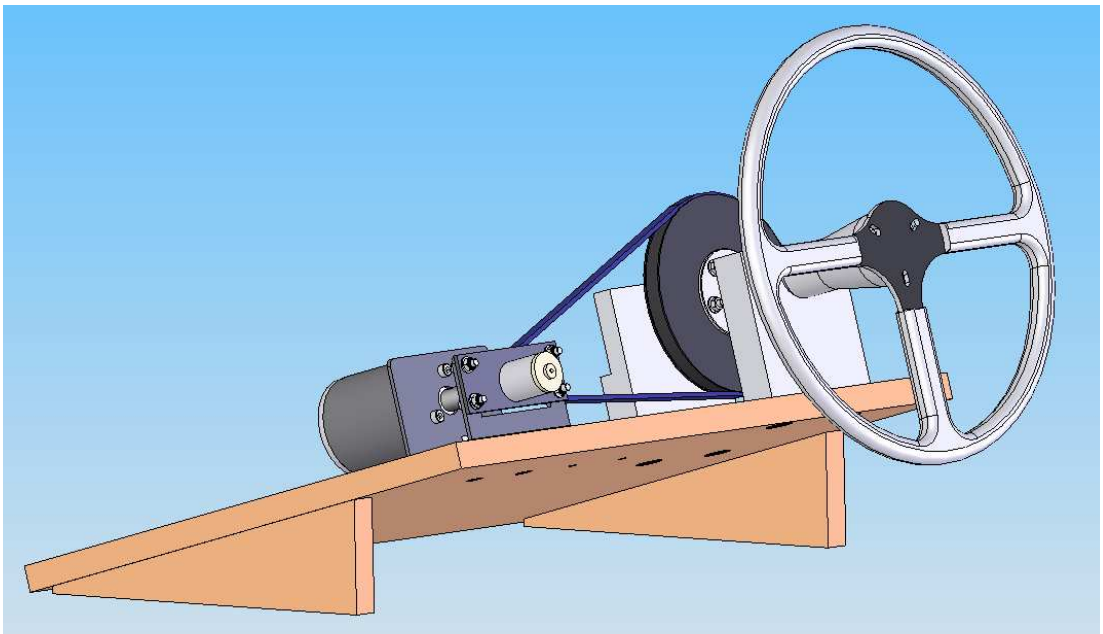

Figure 4.14 3D Model – Completed Assembly

fitting as designed. The exception to this was the circlip that clips onto the main shaft just behind the rear bearing. During manufacture the measurement between the front shoulder on the shaft and the circlip groove was taken as the distance between the front and rear shoulders. The effect of this was that the circlip could not be fitted to the shaft. Since the circlip was included as a ‘safe guard’ and the mechanisms function was unaffected it was decided to use the existing shaft as is. If any part of the mechanism needed to be re-designed and manufactured for functional reasons at a later date then a new shaft could be manufactured including any other modifications that were required.

On completion of the assembly of the device an initial tactile test was done to evaluate the feel the device. The device exhibits a relatively light feel and a slight lumpiness was noted as the motor rotates from one pole to the next, an effect known as cogging, it is not pronounced and does not adversely distract from the overall feel of the device.

The electronics design has also been completed including interface of the sensors to the micro-controller board, selection of 1KW motor driver board. The motor driver board requires a radio-control compatible signal that repeats every 20ms. This may have an effect on quantisation error but at this stage is not expected to be a significant problem. A safety circuit has been designed and constructed to isolate the motor by means of a relay in an emergency situation. The circuits' human interface consists of emergency stop and reset buttons, a red error light and a green device active light. The safety circuit has been tested and functions as designed. From time to time the circuit will immediately trip out when trying to reset the circuit most likely due to electrical noise. At the moment this represents no real problem, but may be rectified later by added some extra filter capacitors or considering the replacing the 74LS TTL logic chips with 74HC series chips that have a wider range of voltages between a logic HIGH and logic LOW.

Chapter 5 Software design and implementation

5.1 Introduction

Software for the project was developed across two platforms and two development environments. A functional approach was taken to the software, the idea being that if the core or functionally necessary parts of the software could be made to work then a complete software solution could be designed and developed based on these core components. The game software was developed with Microsoft VB.net 2008 on a windows based PC while the control and interface software was developed with the Oshonsoft suite of tools for the PIC micro-controller.

Software development was approached from an event or interrupt driven perspective. Rather than the software executing sequentially through blocks of code to produce a certain result, subroutines execute in response to an event or interrupt such as a timer or data being received.

5.2 Micro-controller Software

Since the micro-controller is largely interrupt driven the main program loop becomes very simple as can be seen in the following flow chart. (figure 5.1)
The only real function of the main loop is to call the `send data` subroutine. To ensure the timing of the motor drive signal, 1-2ms pulse, is not interrupted the send data is called in response to a flag bit that is set when the timing of the low part of the pulse begins.

A `calibration` subroutine was included in the initial design, note the dotted line in figure 5.1, but since it forms a non-essential part of the programs operation, it has not yet be implemented. Aside from the peripheral and variable initialisations all other subroutines within the software are called from the interrupt service routine, and are

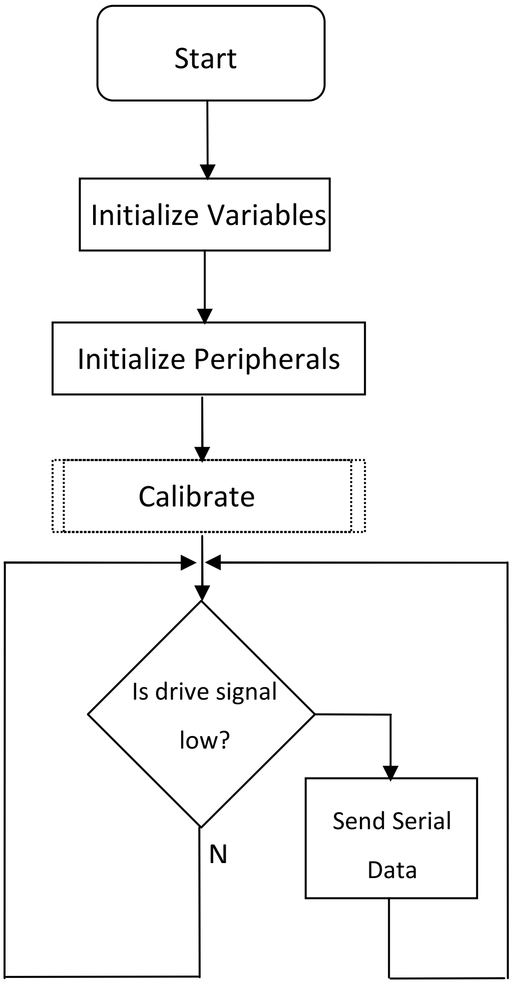

Figure 5.1 Main Loop Flow Chart

centred on the generation of the drive signal timing. Of the numerous on-chip peripherals available the following are used: digital I/O ports, 10-bit analogue to digital converter, serial communications interface and 16bit timer

5.3 Interrupt Structure

Before discussing the generation of the timing signal it is necessary to first understand the micro-controllers interrupt structure. There are 3 control bits associated with the interrupt for each peripheral, an enable bit, a priority bit and an interrupt flag bit. Interrupts are handled according to their priority set as either high or low. Two special subroutines within Oshonsoft Basic handle the interrupts according to their priority. They keywords ON HIGH and ON LOW appear at the beginning of each subroutine. Once an interrupt is triggered and the HIGH or LOW subroutine is called individual interrupt flags must be checked(polled) to determine the source of the interrupt. In the case where only 1 interrupt is enabled, such as in the early development of the code, this checking exercise becomes trivial and thus unnecessary. The priority of each interrupt within their respective HIGH or LOW grouping is determined at the software level. The interrupt flag that is checked first has the highest priority while the second flag in the sequence has second priority and so on until all the flag bits are checked.

Initially it was not understood that the High Priority interrupt enable flag is the same bit as the global interrupt enable, meaning the high priority/Global interrupt enable must be set before the low priority interrupt can be used.

It was originally envisaged that the timer, which generates the control signal, would operate on the low priority interrupt, while a safety button input would operate on the high priority interrupt ensuring the quickest possible response to a safety/emergency situation. It was decided however that a more direct triggering of the safety circuit should be used therefore the timer was set to operate on the high priority interrupt.

5.4 Timer Configuration

Timer1 is used to control the timing of the motor drive signal. The drive signal is dependant on the width of a high pulse in the range of 1-2ms. Theoretically a 1ms pulse results in maximum counter clockwise drive and a 2ms pulse results in maximum clockwise drive while a 1.5ms pulse should cause the motor to stop. The pulse is repeated every 20ms as seen in figure 5.2 that shows a 2ms pulse.

Timer 1 has a resolution of 16bits or a maximum decimal count of 65535. If the interrupt for Timer 1 is set, as in this application, then on reaching its maximum count the interrupt flag bit is set and the timer resets to zero. Since interrupt priority of the timer is set to high, the high priority interrupt flag is also set causing the micro-controller to jump to the high-priority interrupt service routing once execution of the

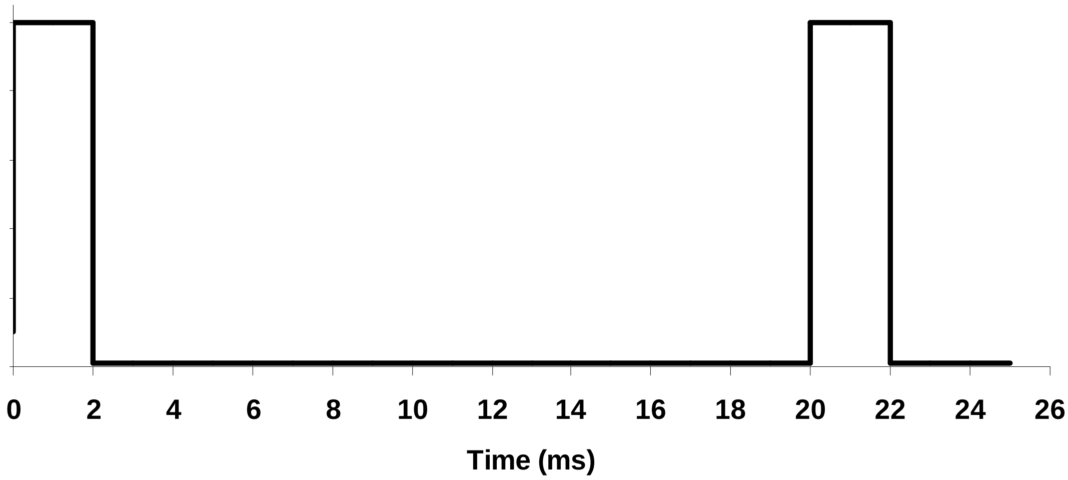

Figure 5.2 2ms Timing Signal

current instruction has been completed. It is possible to write to the timer's counter register and therefore determine the time until an interrupt occurs. For example, say a time is required that is equal to a timer count of 10 000, to cause an overflow after 10 000 counts a value of 55535 (65535-10000) is written to the timer register.

It is also possible to set the frequency or period, of the timer by the timer pre-scaler. The timer pre-scaler has the effect of multiplying the timer's period and can be selected as 1,2,4, or 8. The period of the timer is given as (pre-scaler x 4)/F_{OSC} where F_{OSC} is the oscillator frequency and in our case, 10Mhz

To make best use of the timer, the period should be set so that 20ms represents a count as close as possible to 65535. The ideal period is calculated first where timer period = 20ms / 65535 = 305ns. Using a pre-scaler of 1 the period will be 4/10Mhz = 400ns. The number of counts for a time of 20ms can then be determine 20ms/400ns = 50000 counts. Since the width of the pulse will vary by a maximum of 1ms the number of counts for this period and therefore the resolution of the output signal can be determined by 1ms/400ns = 2500 counts. The resolution of the signal will then be half of that value since its magnitude also determines forward or reverse giving a resolution of ±1250. Table 5.1 shows the relationship between the expected drive output, timing pulse length and timer counts.

Table 5.1 Summary of Timing Signal Relationships

Drive Output	High Timer Count	High Timer Pulse Length	Low Timer Count	Low Timer Pulse Length
Full CCW Drive	2500	1ms	47500	19ms
Stopped	3750	1.5ms	46250	18.5ms
Full CW Drive	5000	2ms	45000	18ms

5.5 Timing Signal Loop

The timing signal subroutine is divided into two sections dependant on the transition of the signal that is either high to low or low to high. If the signal is transitioning from low to high then position and velocity readings are taken, and a new drive signal is calculated by the motor drive calculation subroutine, CALCMD, which outputs the motor drive value. This value is then used tocalculate the timer values for both the high and low times of the pulse before setting the value for the width of the high pulse. When the signal transitions from high to low, the timer is set with the low time and the send data flag is set indicating that the data collected can now be sent.

5.6 Serial Port Communications

To minimise delays in sending the data the micro-controllers maximum baud of 57600bps was used. At this speed given each byte of data will take 1/(57600/8) = 139µs to send. The micro-controller sends data whenever new values are available, it does not wait for a request from the PC thereby avoiding the use of another interrupt and ensuring the integrity of the drive signal. Currently, 3 values are being sent as ASCII requiring 1byte per digit, so for 3 4-digit numbers the maximum expected transmission time will be 1668µs. It should be possible to send the raw data values as 2 bytes per value instead of four. There was however some difficulty with getting VB.net program to work correctly. Should this problem be overcome in the future then the send time should be reduced by 50% to 834µs. Also since the micro-controller has a send buffer, execution of micro-controller functions is not delayed while waiting for data to be sent.

5.7 Control Strategy

A summary of the control strategy is presented in figure 5.3. A full listing of the

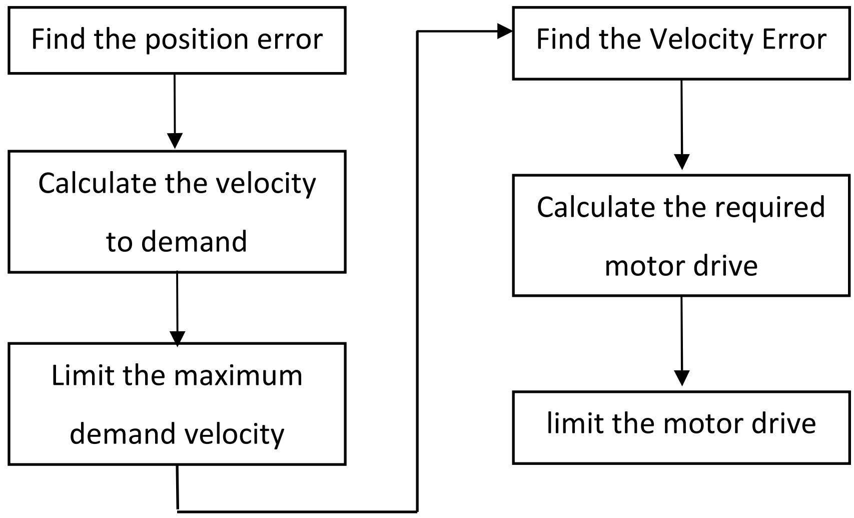

Figure 5.3 Control Strategy Block Diagram

software can be found in appendix D. A number of limitations were involved that increased the complexity of the routine, including the use of positive integers only, and restricting the size of the integers to 16bit to ensure the code executed quickly enough to avoid timing delays

.

5.8 PC Based Software

Two programs were written in VB.net using a similar strategy and frame work but with a very different user interface. Where BMApp was developed as the basis for a top down driving simulator, Signal Trace was written to be used as a development tool for the tuning of micro-controllers control algorithm.

Game Framework

BMApp provides a simple graphics and serial interface that could be used as the basis of a top down driving simulator. All the game graphics are drawn off-screen and then displayed to the screen based on a timer event. This approach provides flicker free animation that is not achievable using a direct draw to screen approach. The curve of the track is defined by an array of values that represent the centre position of the track. This method would allow the shape of the track and therefore the difficulty of the track to be generated by the computer from a set of parameters that could define how sharp bends in the track could be and how often bends need to be negotiated. This type of track generation would allow each level of difficulty to be personally customised to the individual patient's requirements. Control of the car is very simple at this stage, the position of the car being determined by the angle of the steering-wheel, further development of the game is discussed in more detail in chapter 7 under the future work heading. A snapshot of the current game graphics is shown in figure 5.4. The position of the car is updated when the PC receives serial data from the micro-controller, currently once every 20ms.

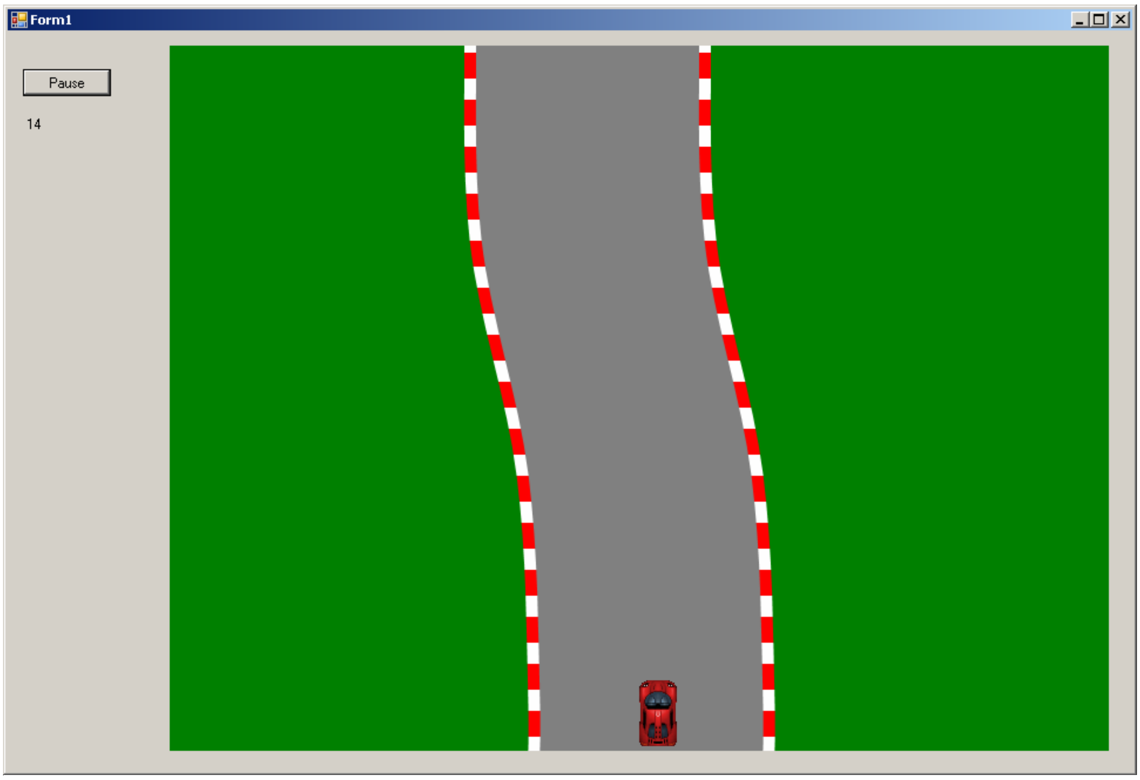

Figure 5.4 Screen Shot of In-game Graphics

Diagnostics Software

The Signal Trace program was developed as a diagnostics tool for the devices sensors and control algorithm. Up to 4 signals can be plotted in real time on the screen, while the values are displayed at the bottom of the window. Note the colours of the screenshots shown have been changed for printing purposes. Typically the plots are displayed on a black background. A slider was also incorporated into the software to vary the trace width from 2s to 20s effectively providing a zoom function on the x-axis. The signal is drawn continuously so that the stepping nature of the digital signal, which is updated every 20ms, can be clearly seen. The short horizontal sections in the trace depict the hold time of signal, while the vertical lines show the signal changing from one value to the next. To create a continuous line the program utilises a system stop

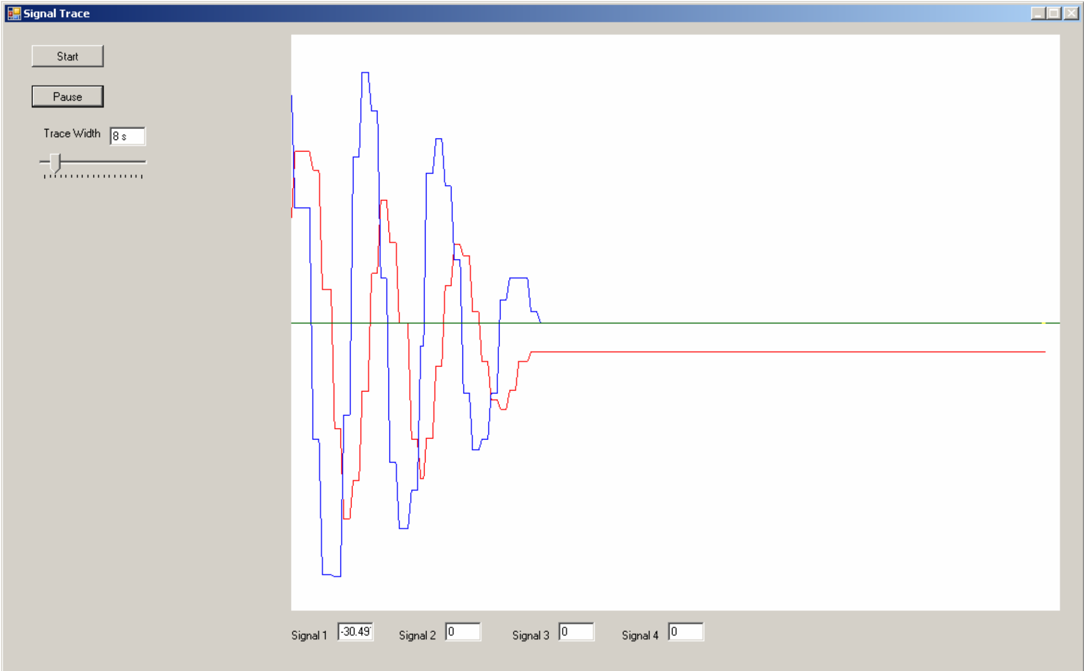

Figure 5.5 Screen Shot of the Diagnostics Software

watch to calculate the elapsed time since the signal was last drawn to the screen. In this way the screen is updated as fast as the PC is able to. This is the same technique used in real-time computer games and ensures the game speed is the same regardless of the speed of the computer. The difference is seen in the quality of the animation.

5.9 Conclusion

While a great deal of work can still be done on the software, the functional objectives have been met. The micro-controller is able to read the sensors, calculate an appropriate drive signal, control the motor and send the data to the PC. The two PC based programs have also been effective with the demonstration of a simple game that can interact with steering-wheel while maintaining flicker free animation. The signal trace software has proved to be a valuable tool in understanding the operation of the system and with a little extra work could be used to receive and log data from any device capable of sending data via an RS232 interface.

Chapter 6 Testing & evaluation

6.1 Introduction

Testing of the device was divided into 4 sections, the first 2 evaluate the inputs of the device, position and velocity while the second two evaluate the outputs, feel and response to drive signal. Where quantitative assessments can be carried out on the inputs relatively easily, the outputs are somewhat more difficult, with more complicated methods of measurement required. Therefore the outputs were assessed from a more qualitative perspective.

6.2 Position Sensor Testing

The position sensor was assessed for both linearity and repeatability. A method of testing was devised where different sized discs could be placed over the steering stop in the rear mounting block to restrict the steering angle. Two different sized discs

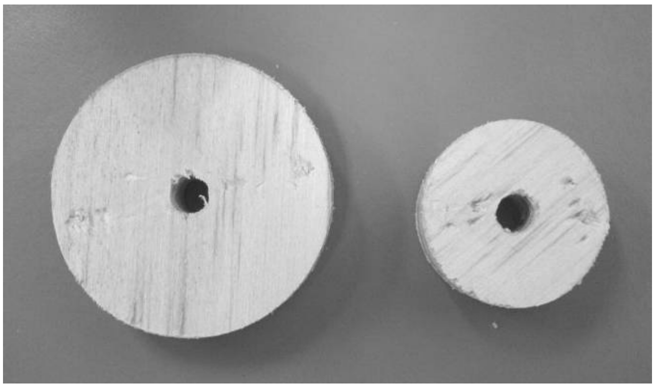

Figure 6.1 - Steering Angle Restriction Discs

were used as shown in figure 6.1, a smaller disc of 30mm and a larger disc of 47mm that were positioned as shown in figure 6.2. The third position used was taken as the maximum lock or steering pin against the stop pin with no disc mounted, while the centre position was aligned by eye as close to 90^{o} as possible.

Figure 6.2 Position of Steering Angle Limiting Discs

The angle of rotation of the steering-wheel when hard against each of the stops was determined graphically. By drawing the steering wheel shaft, limit discs, stop pin and stop dowel, to scale the angles could be measured quickly and easily as shown in figure 6.3. Steering angles are referenced to the steering wheels centre position with clockwise angles measured as positive and counter-clockwise angles measured as negative.

To determine the linearity of the sensors measurements were taken of the resistance of the potentiometer, analogue voltage and value returned from the A/D converter. To check the linearity of the A/D converter an expected A/D value was calculated based

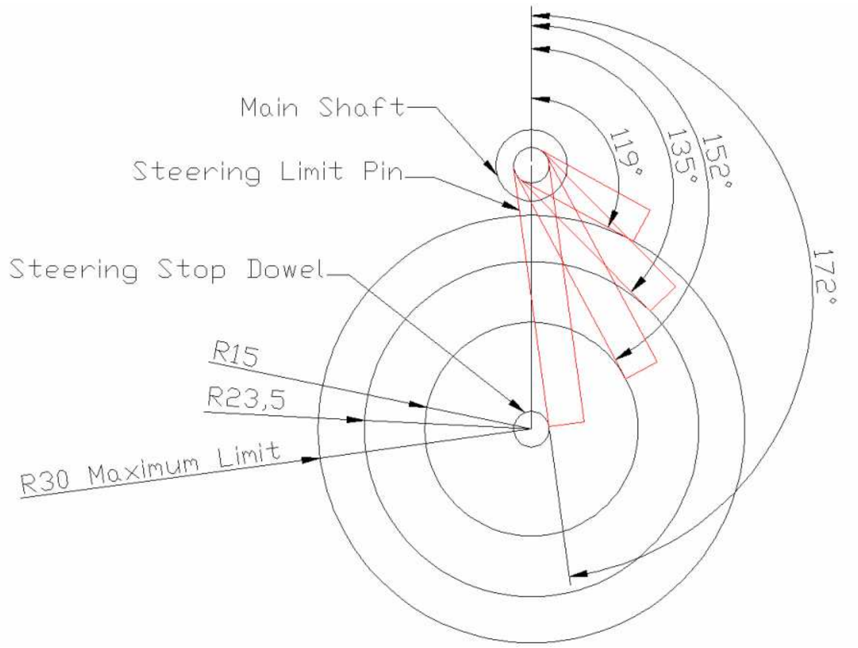

Figure 6.3 Determination of Steering Limit Angles

on the measured voltage and compared to the A/D output. Previously the A/D resolution was determine at 4.88mV/ step, so the A/D value was calculated by dividing the analogue voltage by the Voltage/ step resolution.

Tabulated results are shown in table 6.1, and shown graphically in figure 6.4.

Table 6.1 - Position Sensor Linearity Results

Angle	Measured Resistance	Voltage Measured	Digital Value		
			Calculated	Measured	Error
-172^{o}	0.02	0	0	1	1
-152^{o}	0.59	0.27	55	60	5
-135^{o}	1.05	0.49	100	99	-1
0^{o}	5.25	2.5	512	515	3
$+135^{o}$	9.53	4.53	927	886	-41
$+152^{o}$	9.98	4.74	970	897	-73
$+172^{o}$	10.72	4.94	1011	903	-108

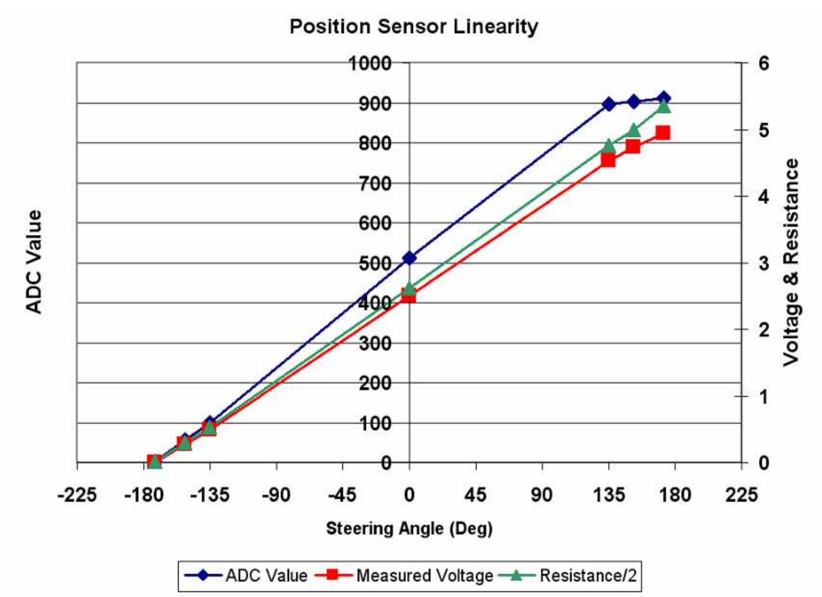

Figure 6.4 Position Sensor Linearity Results

Examining the chart in figure 6.4 it can be seen that both the resistance and voltage output of the sensor have excellent linearity over the full range of measured values. While the ADC values also show excellent linearity up to 132^{o}, beyond that point there is a kink as the slope decreases markedly. At present values read beyond this angle are effectively unreliable and unusable. Since the problem is only exhibited by the ADC value, it was concluded that a linear voltage is input to the A/D converter and that the non-linearity occurs within the A/D conversion process.

On review of the PIC18F458 Data sheet it was discovered that the maximum recommend input impedance of the analogue input the A/D converter, is just 2.5kΩ, well short of the 10kΩ potentiometer used. There is also a leakage current of some 500nA into the input. These two factors combined could explain the lack of linearity beyond 4.5V.
There are a number of solutions that may be tried to prove that the problem is an impedance mismatch and to correct the problem. While the most simple solution would be to replace the current 10kΩ potentiometer with a 1kΩ potentiometer, special order would need to be placed at a not insignificant cost in addition the an expected 4 week plus delivery time. Alternatively the output of the potentiometer could be buffered through an op-amp, which has a very low output impedance, configured as a non-inverting voltage follower as is shown in figure 6.5. To maintain a 0-5V input to the A/D converter a rail-to-rail op-amp should be used. The use of an op-amp buffer is preferred as the most practical solution, however due to time constraints, itis still to be implemented.

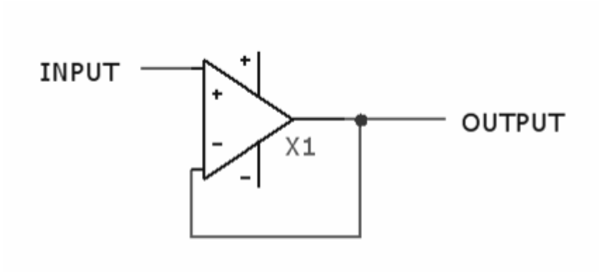

Figure 6.5 Op-Amp Non-Inverting Voltage Follower Configuration

Repeatability Tests

Repeatability is the ability of the sensor or system to produce the same result given identical input conditions. The method of limiting the steering angle with various sized disc, as with the linearity testing, was also employed for the repeatability testing. The centre position was omitted however as this position was set by eye rather than against a hard stop. Ten readings were taken for each of the 6 steering angles to be checked, in between each reading the steering wheel was turned to the opposite lock and back again. The results of the tests are shown in table 6.2.

Table 6.2 Position Sensor Repeatability

	Raw Digital Readings					
Sample	+135°	-135°	+152°	-152°	+172°	-172°
1	897	99	903	56	911	3
2	896	99	903	56	912	3
3	896	99	902	56	911	3
4	896	99	903	56	911	3
5	896	99	903	56	911	2
6	896	100	903	57	911	3
7	896	99	902	56	911	3
8	896	99	903	56	912	3
9	896	99	903	57	911	3
10	896	99	903	56	911	3

The position sensor repeatability test showed excellent results with very little error at any of the angles tested as can be seen in figure 6.6. While it is expected that this level of repeatability will be maintained it would certainly be worth repeating the test after the device has had around 2 hours or more of use.

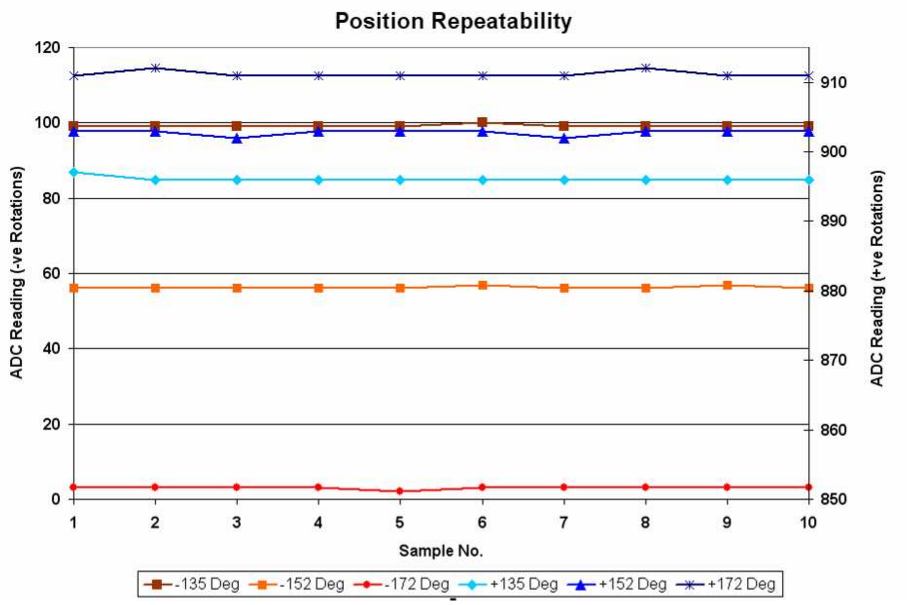

Figure 6.6 Position Sensor Repeatability

6.3 Velocity Sensor

Initial testing of the velocity sensor involved logging of the velocity data during a step response test. A separate piece of micro-controller code, "step response.bas", was written to ensure the test could be repeated under the exact same drive conditions each time. The purpose of the step response test was to determine the length of time the system takes to accelerate to maximum velocity from rest when maximum drive is applied. The systems transfer function could be determined at a later date if a mathematical model was required to simulate the system. The software was very simple, after reset, wait 10 seconds to allow the motor enable relay to be triggered, apply maximum drive to the motor for a period of 2 seconds, turn the motor off. To provide as smooth a response as possible, data was logged at 1ms intervals.

It is evident from the first step response shown in figure 6.7 that the velocity signal

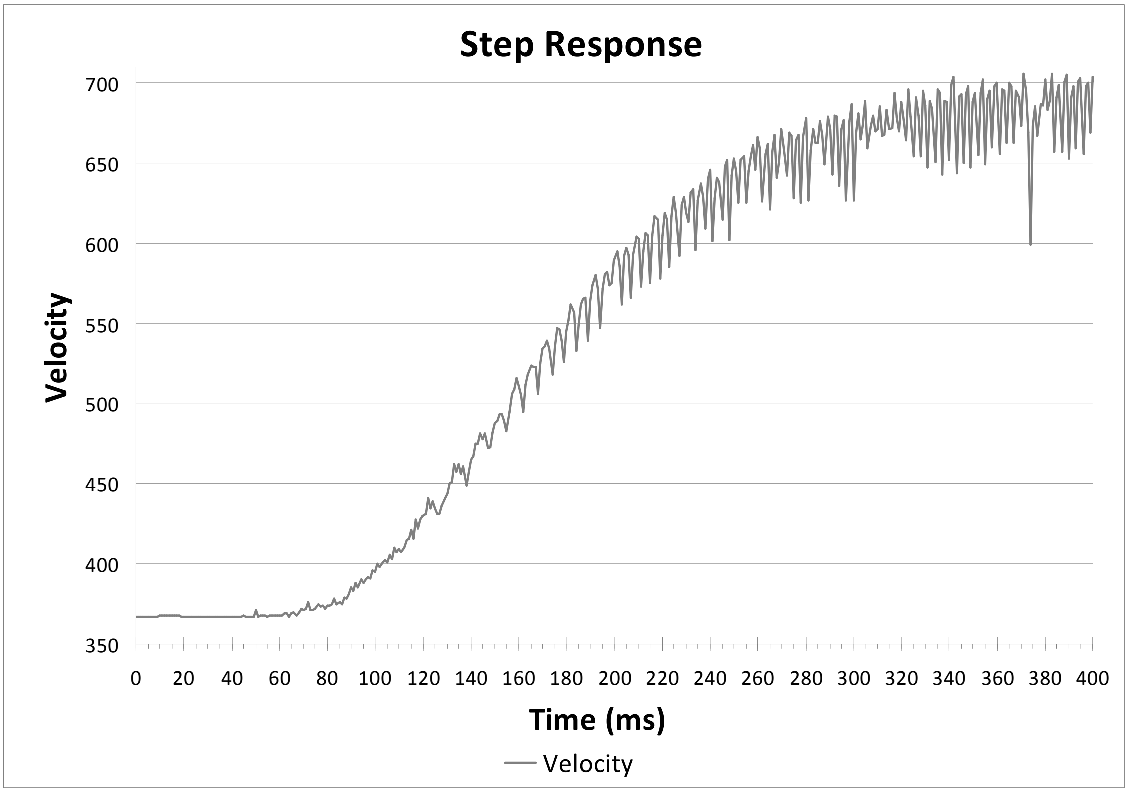

Figure 6.7 Step Response - 1st Test (1ms sample interval)

becomes very noisy as the velocity increases. This type of noise is common to DC motors and is caused by arcing of the commutator. For the signal to be useable some form of filtering would be need to be employed.

Since the step response is slow compared to the frequency of the noise a low pass filter should be used. Noting the cycle time of the noise, a corner frequency of f_c=60Hz was chosen and on the suggestion of the projects co-supervisor a 2nd order low pass Salen-key filter was designed. The general form of the filter is shown below in figure 6.8.

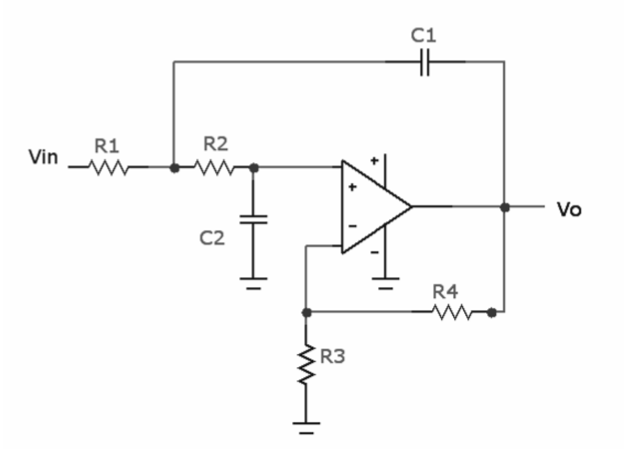

Figure 6.8 Low-Pass Sallen-Key Filter

Since an LM324 quad op-amp was already used to amplify the tachometer signal, three spare op-amps remained unused on the chip and ready for such an application. The equation for the corner frequency is-

$$FSF \times f_c = \frac{1}{2\pi\sqrt{R1R2C1C2}} \quad \text{where FSF = 0.8414}$$

To keep the design as simple as possible the following two initial conditions were set: R1=R2 and C1 = C2. By doing this and rearranging the equation for RC, the new equation becomes.

$$R1C1 = \frac{1}{0.8414 \times f \times 2\pi}$$

$$R1C1 = 3.15 \times 10^{-3}$$

Then by choosing C1 to be 220nF R1 can be calculated

$$R1 = \frac{3.15 \times 10^{-3}}{C1}$$

$$R1 = \frac{3.15 \times 10^{-3}}{220 \times 10^{-9}} = 14330k\Omega$$

So R1 was chosen as 15K. The corner frequency could then be checked

R3 and R4 were chosen to be large so R3 = R4 = 68K.

$$f_c = \frac{1}{0.8418 \times 2\pi R1C2} = \frac{1}{0.8418 \times 2\pi \times 15k \times 220nF} = 57Hz$$

The complete tachometer interface circuit with sallen-key filter is shown below in figure 6.9. The circuit was constructed on the breadboard area of the micro-controller as seen in figure 6.10.

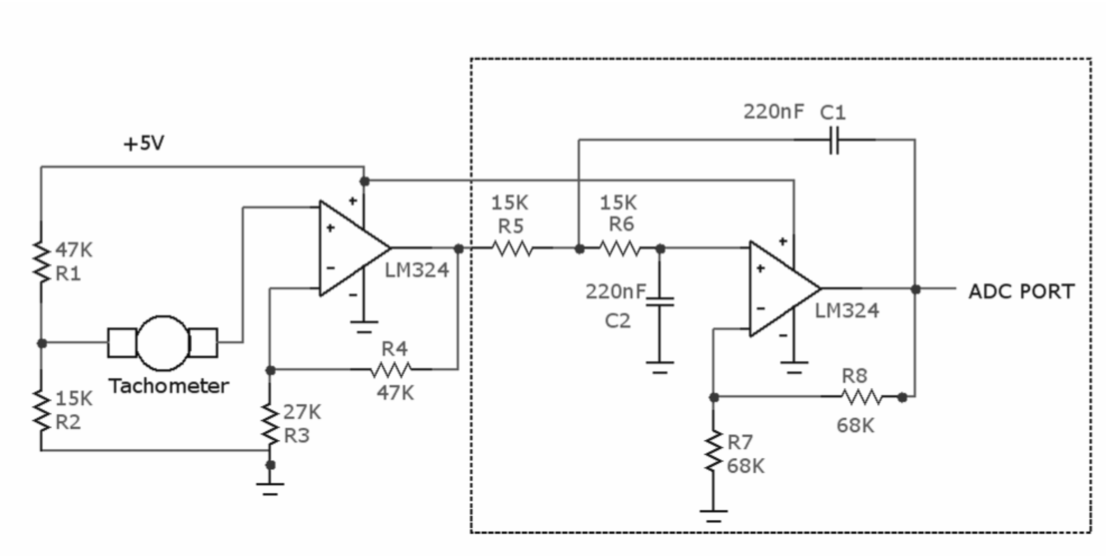

Figure 6.9 Tachometer Interface with Low-Pass Sallen-Key Filter

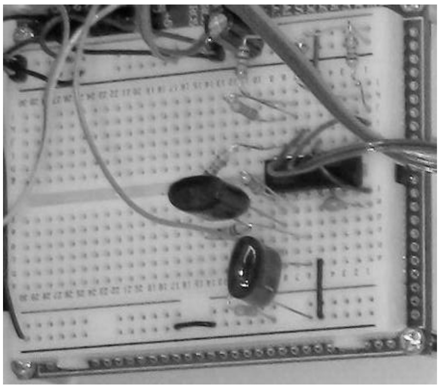

Figure 6.10 Construction of the Tachometer Interface Circuit

After construction of the filter circuit the step response test was repeated. As can be seen in figure 6.11 the circuit works extremely well, with a dramatic reduction in noise. It is estimated that noise in the signal has been reduced from 10% to around 1%, greatly improving the quality of the signal. While some lag does occur in the signal at around 100ms, it is very minor and is not expected to affect performance. Based on the new filtered signal the step response time can determined at 320ms

A second analysis of the data was done to determine the extent of the affect of quantisation error for a change in sampling frequency from 1kHz to 50Hz. While the same data for the filtered signal is used in the comparison the 50Hz plot, shown in red, takes every 20th value. Examining figure 6.12, on the following page, it can be seen that a change in sampling should not have a significant impact on the quality of the signal.

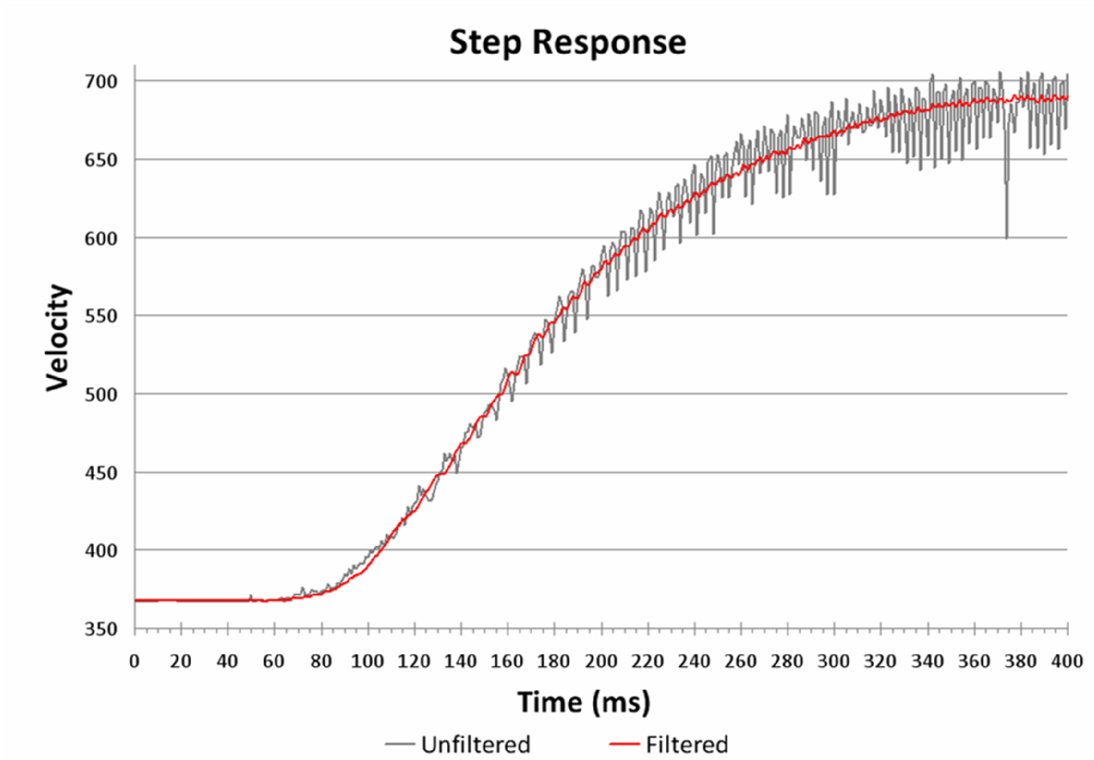

Figure 6.11 Filtered vs Unfiltered Step Response

The tachometer and its interface circuit were also tested for linearity including the A/D conversion. Six drive signals were used, three for clockwise rotation and 3 for counter-clockwise rotation, with voltages measured at node 1 - the input to the first op-amp, node 2 - the output of the first op-amp and node 3- the output from the second op-amp. The ADC value was also taken, with the results shown in the table below

Table 6.3 Tachometer Test Results

		Analogue Voltages			
Input Signal	Digital Pulse Width	Node 1	Node 2	Node 3	Digital Reading
CCW	500	0.2	0.32	0.31	60
CCW	700	0.29	0.44	0.44	152
CCW	900	0.63	0.95	0.94	295
Stopped	1100	1.2	1.8	1.8	384
CW	1300	1.88	2.83	2.82	543
CW	1500	2.19	3.26	3.26	624
CW	1700	2.25	3.39	3.38	711

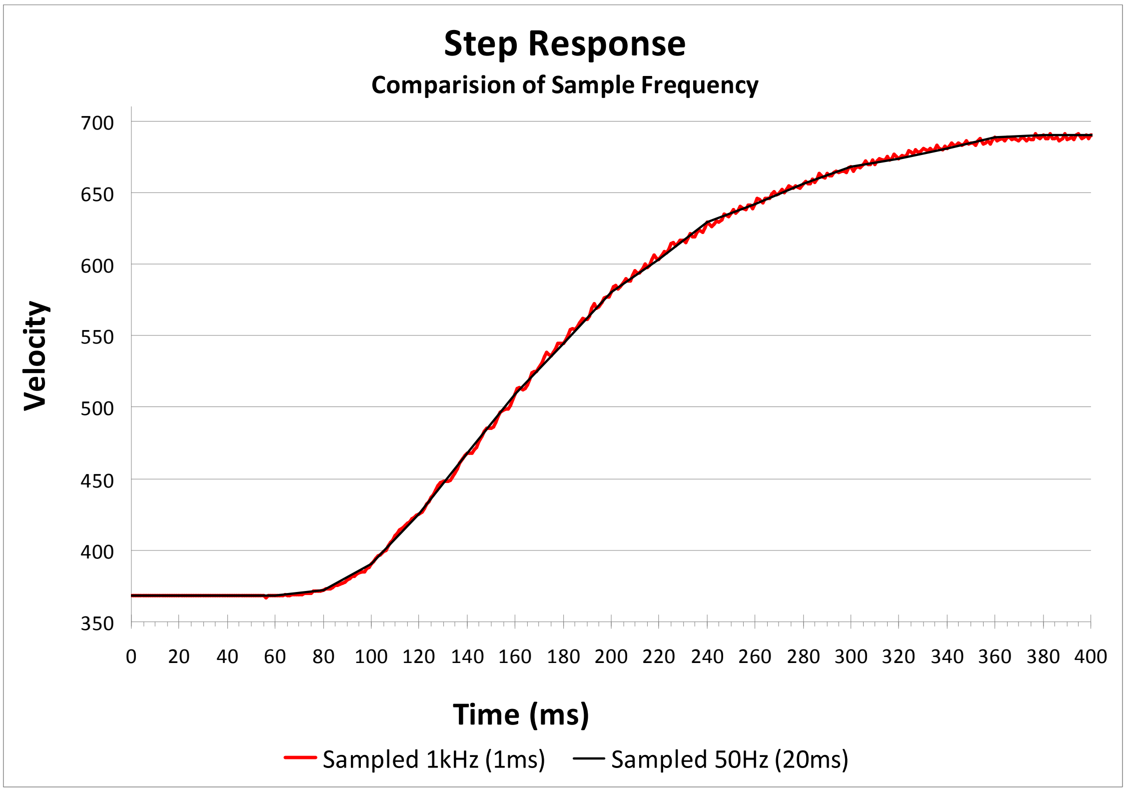

Figure 6.12 Comparison of Sampling Frequency

While an initial inspection of the results in figure 6.13 tends to indicate that the velocity sensor behaves in a non-linear manner, it is worth discussing the possible sources of the non-linearity before drawing a conclusion. The drive signal is perhaps not the best reference for the velocity sensor given the path of the drive signal from the micro-controller and through the motor driver board. The drive signal value is first converted to a timing pulse with a length of 1-2ms with a resolution of 400ns by the micro-controller. The motor driver then converts the pulse to an analogue voltage that is used as a reference to determine the duty cycle of a 300Hz PWM drive signal that switches the FET's. Assuming that each process behaves in a linear manner it is still possible that the motor driver is applying the full range of drive for a timing pulse width narrower than 1-2ms, say 1.2 to 1.8ms. This being the case a drive signal outside this range produces no change in the motor drivers output and therefore no change in velocity.

The behaviour of the motor should also be considered. The velocity of a motor does not respond in a linear manner with respect to the applied drive voltage, but it tends to roll off as it peaks out at maximum velocity. Therefore assuming the effective drive voltage applied to the motor is linear with respect to the drive signal then the results fit quite well showing noticeable roll off as the motor approaches maximum velocity in both directions.

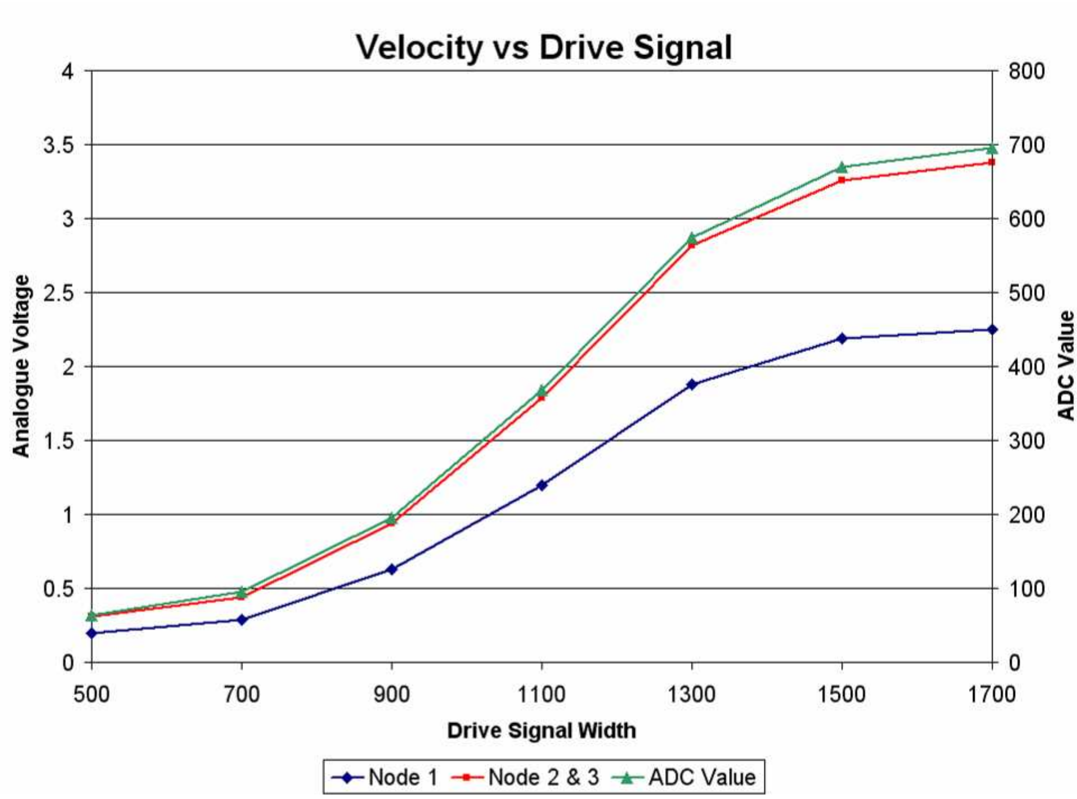

Figure 6.12 Velocity Signal Linearity Analysis

To determine the true nature of the velocity sensor a different method of testing is necessary. The output of the velocity sensor should be compared to a 'real' velocity reading that could be taken with a hand held optical tachometer. To provide more conclusive results it would be recommended to take 10 velocity measurements in both directions at drive signal intervals of 100 beginning with the motor stopped signal

6.4 Motor Control Testing

A pragmatic approach was used to test the response of the motor driver board to the timing signal generated by the micro-controller. With the drive belt disconnected the ADC reading from steering position sensor could be used to vary the pulse width. Since the ADC has a maximum output value of 1024, and the drive signal requires a maximum value of 2500, the value from the position sensor was simply multiplied by 2. The driver board and motor responded as expected, with the motor rotating at maximum counter-clockwise velocity near a drive signal value of 0, motor stopped at a value of 1100 and maximum clockwise velocity near 2048. Maximum velocity was determined by listening to the pitch of the motor, when no change in pitch occurred the motor had reached maximum velocity.

It was noted however that a significant dead-zone was present. For drive signals of 1100 ±150, no drive occurred. The schematic for the motor driver board notes that the 15K resistor R22, see appendix C, affects the dead-band. This was corrected by replacing R22 with a 20K 25 Turn cermet variable resistor. A 25 turn cermet was chosen over a single turn potentiometer to give as precise an adjustment as possible. Due to wider terminal leg spacing the cermet could not be mounted directly on the board, therefore short extensions were made to allow it to be fitted. The cermet, rectangular shape, can be seen clearly in Figure 6.14
While the solution is not very elegant, the results were very good with the dead band reduced to ±10, a reduction in dead band from 15% to 1%.

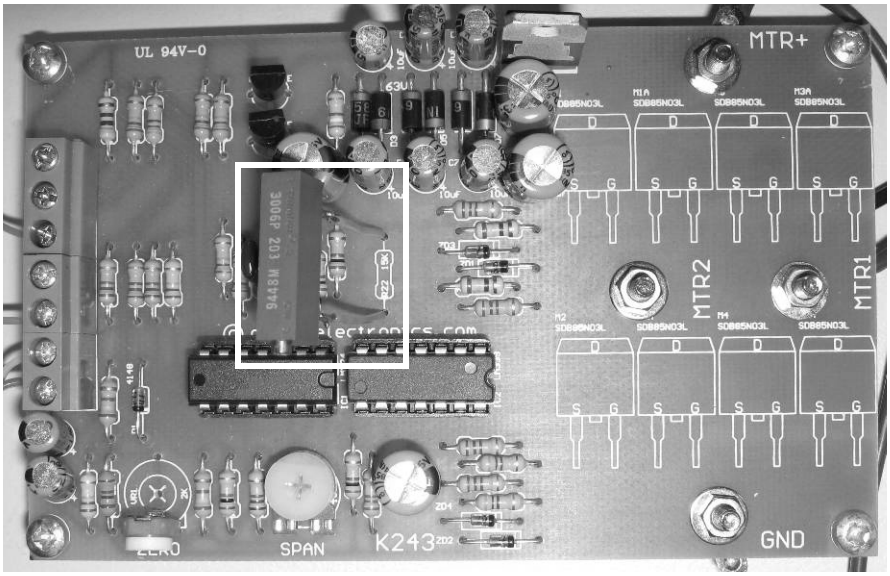

Figure 6.14 Driver Board with Cermet Modification

6.5 Device Evaluation

The device was evaluated in two key areas, feel and ability to provide feedback, and self centering. The feel of the device is very good, the cogging or lumpy feel noted in chapter 4 is not noticeable when the motor is be actively driven as a feedback device.

With the control system developed, the feel of the steering can be varied over a wide range from very light to very strong and could be applied as either resistance or assistance depending on the requirements, although only resistive feedback has been evaluated at this point. The maximum strength of the feedback, while not yet quantified, is very good and should be more than enough. The effort required to overcome the maximum resistance compares well, from a subjective viewpoint, with the effort required to turn the steering wheel of a power-steering equipped 2003 Hyundai Getz with the vehicle stationary and brakes applied. It should also be noted that at no time during testing was there any indication of the motor or driver board temperatures rising above ambient. It would be prudent of course to conduct a more prolonged test of 10-15 minutes while monitoring their temperatures to ensure the device can operate safely without the need for cooling.

6.6 Self-Centering Tests

A series of self centering tests were done using, making changes to the velocity gain and or position gain, in an attempt to have the device self centre without overshoot. See chapter 5 for a description of the control algorithm. The signal trace program, also in chapter 5, was used to plot and then capture the response of the system. The desired time-position response curve is shown in figure 6.15 and is termed a critically damped response.

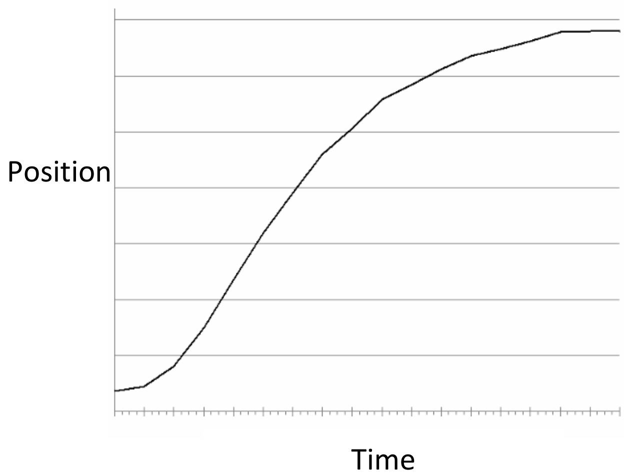

Figure 6.15 Critically Damped Response

While the best result was obtained with feedback gains of 6 for both position and velocity the response still falls short of the desired response. Figure 6.16 is a composite image that shows a trace of the position, red line, and the velocity, blue line. The trace to the left shows the response from a larger error than the response on the right. In both cases the device overshoots significantly before reaching a steady state but with significant error, the distance between the red position and the green centreline.

Figure 6.16 - Centering Response (composite)

When the initial error is large, left-hand trace, the device oscillates badly several times before reaching a steady state showing a significantly underdamped response. This should be overcome by increasing the velocity gain. When the velocity gain is increased to 8 however, the device becomes unstable oscillating in an undamped manner as shown in figure 6.17.

It is suspected the low frequency of the drive signal prevents any further improvement of the systems response. Since the motor driver only accepts a new signal every 20ms the drive signal is 1/20ms = 50Hz. The short horizontal lines in the traces, such as figure 6.15 are the hold time or the 20ms period in between sampling of the position and calculation of a new drive signal. Note in the left hand response of figure 6.15 that when successive samples appear on opposite sides of the centreline, this means that the steering-wheel has rotated too far during the 20ms period and gone past centre and must come back again. To gain a further insight into the issue position readings were taken with the motor just turning. That is the drive signal was slowly increased until the motor just started to turn. At this speed the average change in position readings over 20ms was 30 counts. Since we know that each count measures 0.33^{o} of rotation then the change in angle for 30 counts will be 10^{o}. Therefore the response of the system cannot be improved any further in its current configuration.

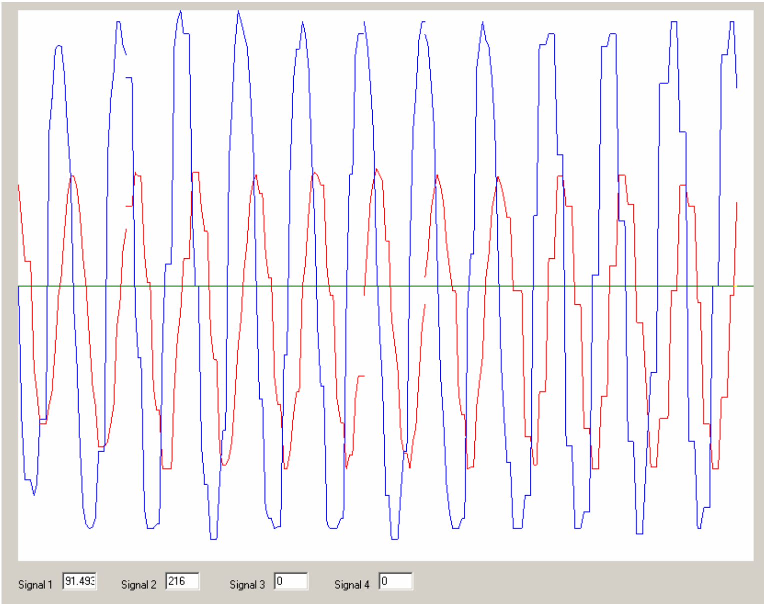

Figure 6.17 Oscillating Response

The solution to this issue is thought to be a shorter drive signal timing interval. That is a higher drive signal frequency. To evaluate the effects of a higher frequency, drive signal timing was recalculated so that intervals of 5, 10 and 15ms, frequencies of 200Hz, 100Hz and 67Hz, could be tried. Unfortunately when a control signal was applied at any of the proposed test frequencies the motor could not be controlled at all, full drive was applied to the motor regardless of the drive signal. It was therefore not possible to determine the effect of increasing the control signal frequency. There are a number of other possible solutions for improving the response of the system but these will be discussed in the further work section of chapter 6.

6.7 Conclusion

While testing of the device has presented some issues, there is a general understanding of the cause and some suggestion made to overcome them. The position sensor itself shows excellent linearity and repeatability. While the conversion to a digital value does show some non linearities the problem is most likely caused by an impedance mismatch and should be able to be fixed by buffering the input with and op-amp. It is difficult to draw conclusions about the linearity of the velocity sensor with more testing required. The behaviour of the sensor does seem to be linear however when the drive characteristics of the motor are considered.

The timing signal from the micro-controller is able to control the speed of the motor, which effectively translates to controlling the force. While a large dead band was initially present this has been overcome by a simple modification to the motor driver board.

Evaluation of the device has proved it to be capable of providing a range of resistive feedback torques. While measurements of the maximum torque produced are not available a subjective assessment indicates that the device at least comes close to providing the 5Nm design torque. Additionally the relative feel of the device is very good and does not suffer from heavy feel of commercial controllers.

A method of centering of the steering-wheel has been developed and the general control strategy shown to be capable of controlling the device. Unfortunately due the low frequency of the control signal a satisfactory centering response could not be achieved. The low frequency issue stems from the input requirements of the motor driver board, which will need to be modified or replaced before the centering response can be improved.

In general testing of the device has been promising, this is especially so in the overall feel of the device and the ability to control or vary the feel. Importantly the device has been successfully interfaced to the PC and is able to interact with a simple game environment.

Chapter 7 Conclusion and Future work

7.1 Conclusion

The literature review has shown that there are great benefits to be had from the use of haptics devices and virtual reality environments in the context of stroke patient rehabilitation. These types of devices are able to hold the patients interest and keep them motivated. Importantly the devices are able to provide data about patient progress. Unfortunately, with the exception of T-WREX, most of the devices are only suitable for research work, or use within a rehabilitation clinic. T-WREX is well on the way to being developed into a system suitable for use in the home.

Driving simulators have significant benefits for driving retraining over conventional methods that included cognitive therapy and potentially dangerous on road retraining. It is not suggested that a simulator replace on road training, but rather be used as a safer intermediate tool to provide assessment of the patients progress and ability before venturing out onto the open road. There is a need then for a force feedback steering wheel and driving simulator designed specifically for use within the context of stroke patient rehabilitation. This is especially so of devices suited for either supervised use in a rehabilitation clinic, or unsupervised use in the patients' home.

An initial system concept was developed, outlining the various modules that make up the system before discussing the suitability and shortcomings of the shelf game controllers. These short comings include a limited range of rotation and a poor or overly heavy feel. Additionally the controllers are difficult to access from a software perspective requiring a high level expertise in the area to understand device drivers and Direct-X programming.

The design requirements of the device have been defined, in order to make the device suitable for use in a rehabilitation environment. More specifically the device needs to be able to provide a feedback torque of up to 5Nm while remaining relatively smooth. The device also must have the ability to collect data to assist in rehabilitation, and to that end the device must be small enough and cost effective enough for use in rehabilitation clinics or in the home.

A number of methods of providing the feedback were examined, including the use of hydraulics, pneumatics, slipping clutches and electric motors. An electric motor was chosen as the most feasible solution for this application due to their controllability, relative compactness and cost. Having determined an electric motor should be used the selection of a h-bridge based motor driver board follows logically as the best method of providing bi-directional control.

It was also determined that, in terms of range of angle, precision and ease of reading that a continuous potentiometer would be the best sensor for reading the steering wheel angle. A small DC-motor was then selected as a velocity sensor to directly read the steering rate rather than rely on derived velocity signals from devices such as hall-effect sensors or other types of position sensors.

While the first choice in interface electronics was the Velleman USB Extended interface board, the cost, availability and risks associated with the construction of the board meant it was an unviable solution. An alternative was found in the selection of PIC18F458 development board that provided a good level of performance and flexibility while remaining cost effective.

With the exception of the choice of interface circuitry, selection of specific components has been avoided in the conceptual design phase. After careful consideration of the previous discussion the following '*modules*' were chosen for development into a prototype.

Feedback Source	Single Permanent Magnet DC Motor 0.5Nm Stall Torque
Power Transmission	Toothed Drive Belt
Position Sensor	Continuous Potentiometer
Velocity Sensor	Small DC Motor as a tachometer
Torque Sensor (optional)	Shunt Resistor
Interface Electronics	PIC 18F458 Prototyping Development Board

Drive Circuitry	Off the shelf H-Bridge, kit or module 12V 20A

A 100 watt 24V motor from an electric scooter was chosen to provide the feedback torque. With timing pulleys, belts selected to give a gear ratio of 8.4:1 the system should be able to provide a peak feedback torque of 4.8Nm. Having created detailed 3D models of the purchased components the remaining mechanical components were designed and assembled into a 3D assembly model before creating detail drawings of the components for manufacture.

Assembly of the mechanical system was very straight forward with most components fitting as designed. The only exception was a circlip that could not be fitted due to an error in the manufacture of the main shaft. It was possible to use the shaft as it was, therefore if the shaft needed other changes for functional reasons at a later date then a new shaft could be manufactured including those changes.

On completion of the assembly of the device an initial tactile test was done to evaluate the feel the device. The device exhibits a relatively light feel and a slight lumpiness was noted as the motor rotates from one pole to the next, an effect known as cogging, it is not pronounced and does not adversely distract from the overall feel of the device.

The electronics design has also been completed including interface of the sensors to the micro-controller board, selection of 1KW motor driver board. The motor driver board requires a radio-control compatible signal that repeats every 20ms. This may have an effect on quantisation error but at this stage is not expected to be a significant problem.

A safety circuit has been designed and constructed to isolate the motor by means of a relay in an emergency situation. The circuits' human interface consists of emergency stop and reset buttons, a red error light and a green device active light. The safety circuit has been tested and functions as designed. From time to time the circuit will immediately trip out when trying to reset the circuit most likely due to electrical noise. At the moment this is a minor issue represents no real problem for the function of the device.

While a great deal of work can still be done on the software, the functional objectives have been met. The micro-controller is able to read the sensors, calculate an appropriate drive signal, control the motor and send the data to the PC. The two PC based programs have also been effective with the demonstration of a simple game that can interact with steering-wheel while maintaining flicker free animation. The signal trace software has proved to be a valuable tool in understanding the operation of the system and with a little extra work could be used to receive and log data from any device capable of sending data via an RS232 interface.

Testing of the device has presented some issues, there is a general understanding of the causes and some suggestions have been made to overcome them. The position sensor itself shows excellent linearity and repeatability. While the conversion to a digital value does show some non linearities the problem is most likely caused by an impedance mismatch and should be able to be fixed by buffering the input with and op-amp. It is difficult to draw conclusions about the linearity of the velocity sensor with more testing required. The behaviour of the sensor does seem to be linear however when the drive characteristics of the motor are considered.

The timing signal from the micro-controller is able to control the speed of the motor, which effectively translates to controlling the force. While a large dead band was initially present this has been overcome by a simple modification to the motor driver board.

Evaluation of the device has proved it to be capable of providing a range of resistive feedback torques. While measurements of the maximum torque produced are not available a subjective assessment indicates that the device at least comes close to providing the 5Nm design torque. Additionally the relative feel of the device is very good and does not suffer from heavy feel of commercial controllers.

A method of centering of the steering-wheel has been developed and the general control strategy shown to be capable of controlling the device. Unfortunately due the low frequency of the control signal a satisfactory centering response could not be achieved. The low frequency issue stems from the input requirements of the motor driver board, which will need to be modified or replaced before the centering response can be improved.

In general, the testing and evaluation of the device has been promising, this is especially so in the overall feel of the device and the ability to control or vary the feel. Importantly the device has been successfully interfaced to the PC and is able to interact with a simple game environment.

7.2 Future Work

There is a large amount of work to be done before the device could be demonstrated or tested in a rehabilitation environment.

The most pressing issue is the self centering of the device. There are a number of ways that this could be improved. As a first attempt the components on the motor driver board that limit the control signal frequency to 50Hz, should be changed to allow a control frequency of up to 200Hz. Alternatively the motor driver PCB could be modified to allow two outputs from the micro-controller board to directly control one half of the h-bridge each, allowing a much simpler drive signal to be used. It may however be more practical to purchase or construct a different h-bridge that will allow direct control. A pair of BTN-7970 Half bridge chips are available from Mouser Electronics at around $10 each and would provide a suitable solution.

The motor could be replaced with a motor than can operate at a lower speed however this could be somewhat difficult to provide. Alternatively a damper could be added to the system effectively providing a speed limit. This could be as simple as a leather belt pulled tightly over the shaft or a rotary fluid damper which would be likely to produce better results. Improve the systems self-centering response.

An LMV824 rail-to-rail op-amp has been purchased and installed in the tachometer interface circuit to provide a full 5V range output however the gain of circuit needs to be recalculated and the appropriate resistors replaced for increase in range to be realised. There are two spare op-amps available on the chip, one of which can easily be used as a buffer for the position sensor to over come the impedance mismatch issue therefore remove the non-linearity observed at the upper end of the sensors range.

The software represents the largest area of the project for development. Currently the steering wheel affects the position of the car on the screen. Using the current top down framework the control could be modified so that the angle of the steering wheel affects that rate of turning of the car to provide more realistic control. The software could then progress in either the development of game play and data logging or the move to a full 3D graphics simulation. Facilities should also be developed in the software to allow the feedback strength to be set. Additionally if a new *centre* position was set at the angle necessary to negotiate a turn then the steering wheel could effectively be made to self-drive. To move to other forms of assistive or resistive feed back should follow on from this with little difficulty.

A very important aspect to the future work is the development of a method of scoring the drivers ability and progress. Since stroke patients often have difficult with fine motor control and tend to over correct the car or swerve, it is suggested that the scoring be based on swerve severity and swerve frequency. Measuring the distance from car to the centre of the track is of little use. However, if this measurement is used to determine the rate of change of distance to the centre line, then this would shows how steeply or aggressively the centre line is approached. When this rate of change goes from positive to negative this would indicate that the vehicle has gone from moving away from centre to moving towards centre, if the change is sharp enough then this would represent a swerve. By then monitoring how severe and how often swerves are made a score could be determined and compared to known baseline of an average driver. How often swerving occurs would determine swerve frequency, poor motor control should result in high swerve severity and frequency while average driver should show low swerve severity and frequency, that is very little swerving is done and corrections are made gently as opposed to suddenly. It is expected that filtering an analysis of the raw data will be necessary to achieve this but is difficult to predict until real data is collected.

Future work could also include the trial of an optical encoder to facilitate the move towards a device capable of multiple turns lock to lock. It would also be beneficial to develop a single custom designed PCB containing micro-controller, safety circuit and h-bridge to move towards a more production level device. To that interfacing of the device should be changed from RS232 to the more universally accepted USB interface.

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Appendices

Appendix A Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

<u>ENG4111/4112 Research Project</u>
Project Specification

FOR : **GEOFF O'SHANNASSY**

SUPERVISOR: Dr. Selvan Pather

PROJECT AIM: To investigate the use of computer games and haptics devices in the area of stroke patient rehabilitation. Design and develop a force feedback steering wheel and driving simulator for the purposes of stroke patient rehabilitation, providing useful data as an indicator of patient progress.

PROGRAMME: Issue A, 12 March 2009-03-12

1. Research the use of computer games and haptics devices in the area of stroke patient rehabilitation.
2. Design a force feedback steering wheel with the capability of providing passive resistance, active resistance and active assistance.
3. Select and implement the associated electronics for data collection, feedback application and interface to a Windows based PC.
4. Develop a software based position controller to provide passive resistance.
5. Design and code a simple computer game capable of taking measurements relevant to patient rehabilitation progress making raw data available for further processing.

As time permits:

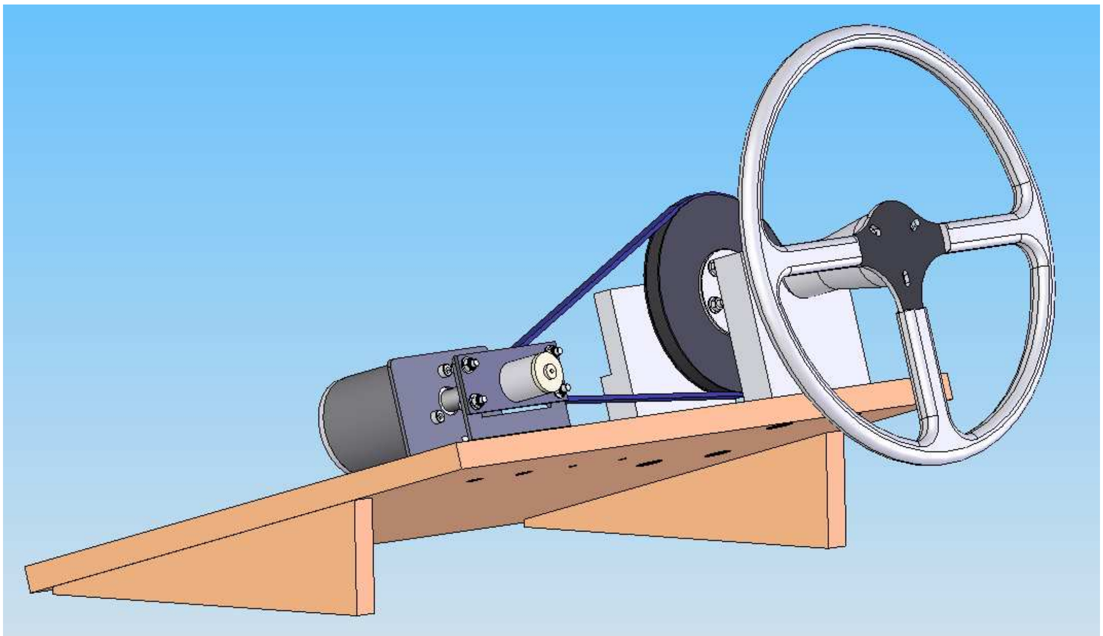
6. Create a simple 2D driving simulator
7. Investigate and develop methods of providing active resistance and active assistance.
8. Add in program data reporting.

AGREED:

Signed ________________________ Geoff O'Shannassy Date ___/___/______ (student)

Signed ________________________ Dr. Selvan Pather Date ___/___/______ (supervisor)

Appendix B Assembly Drawings and Device Photos



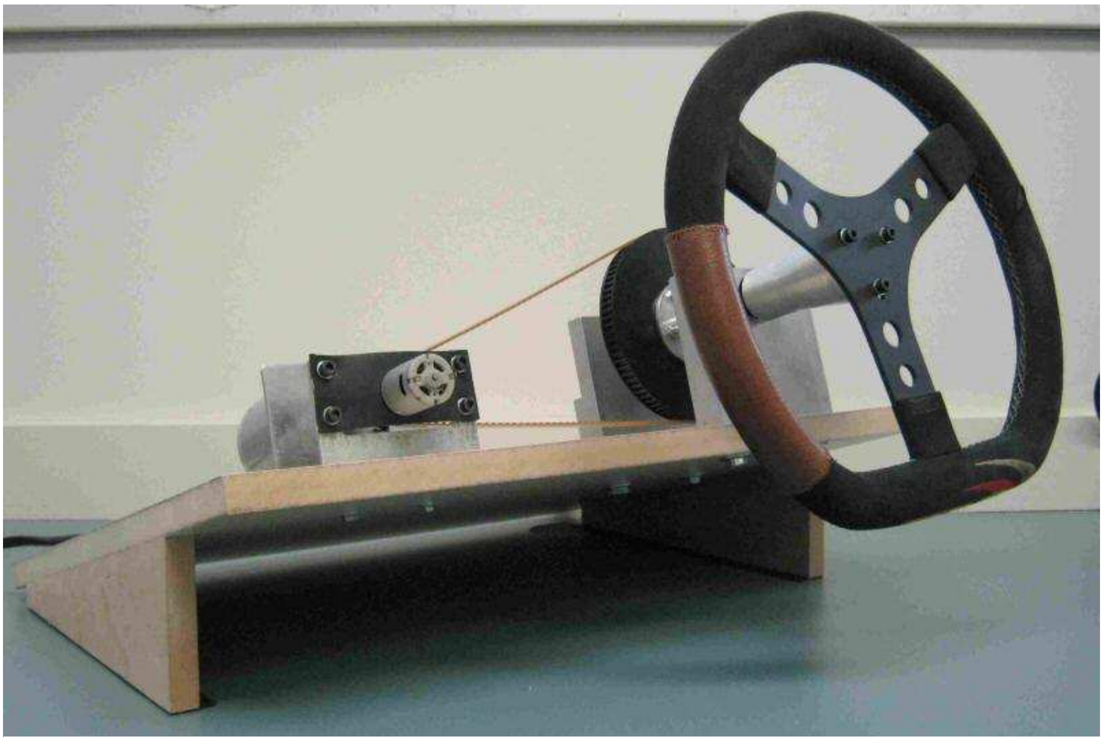
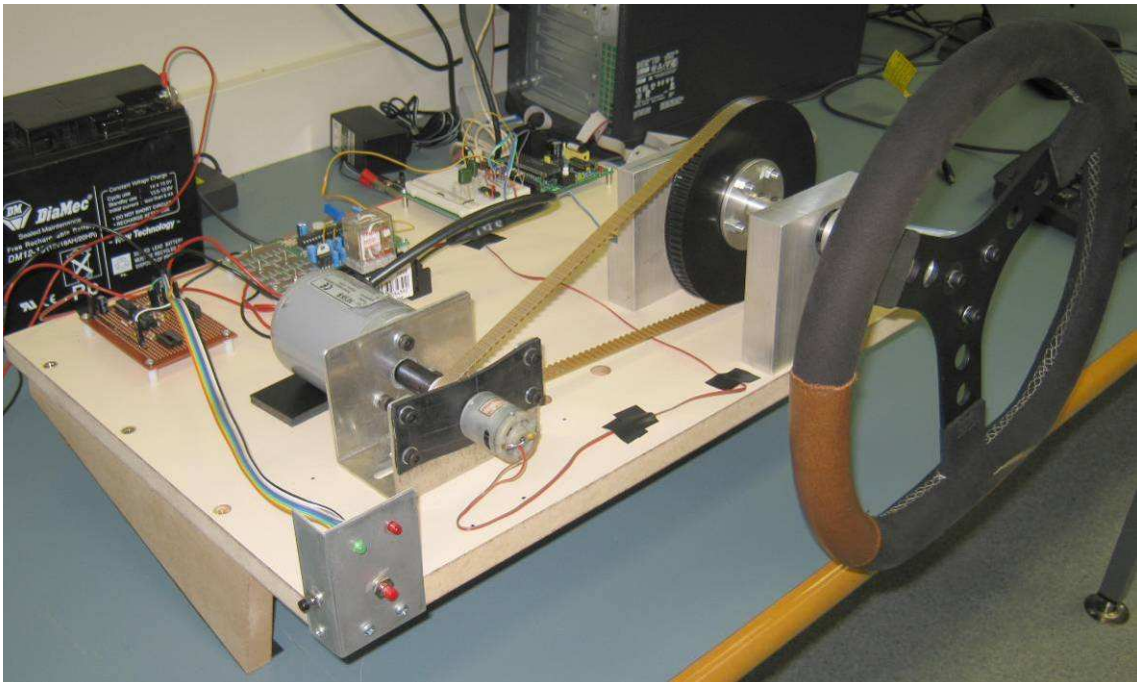
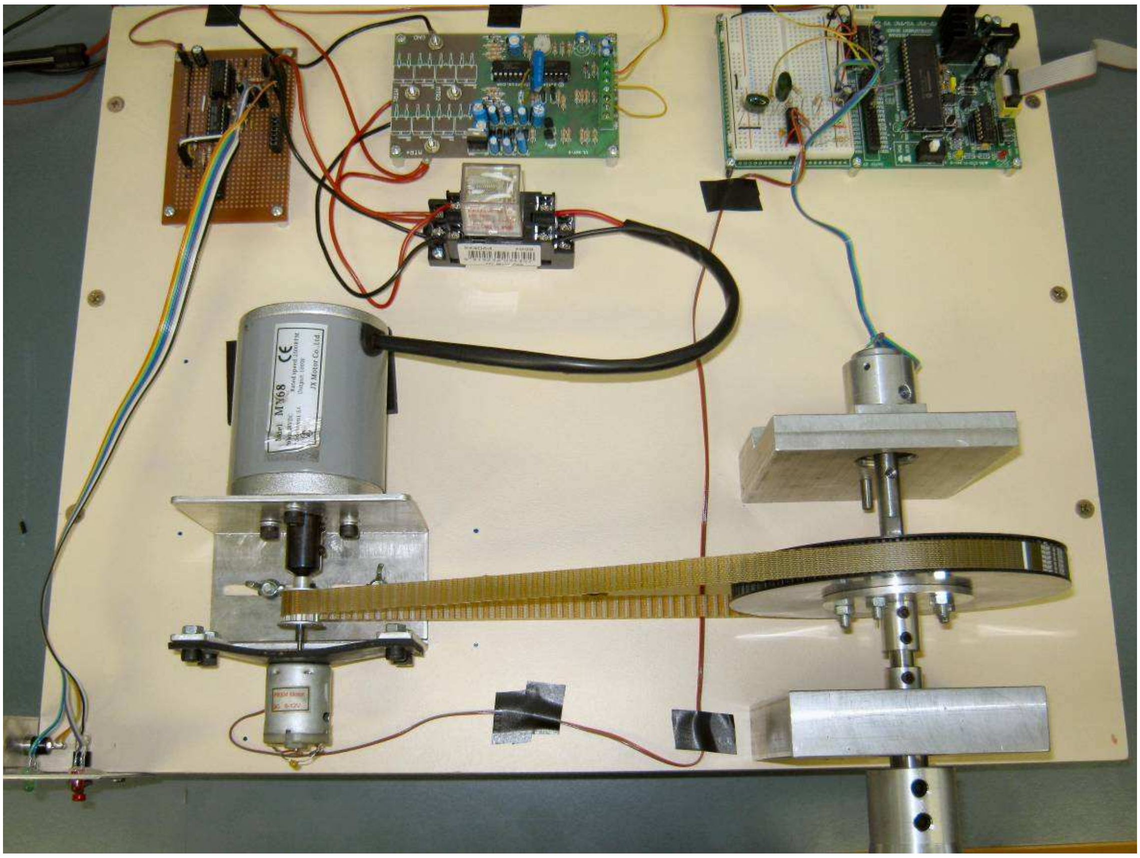
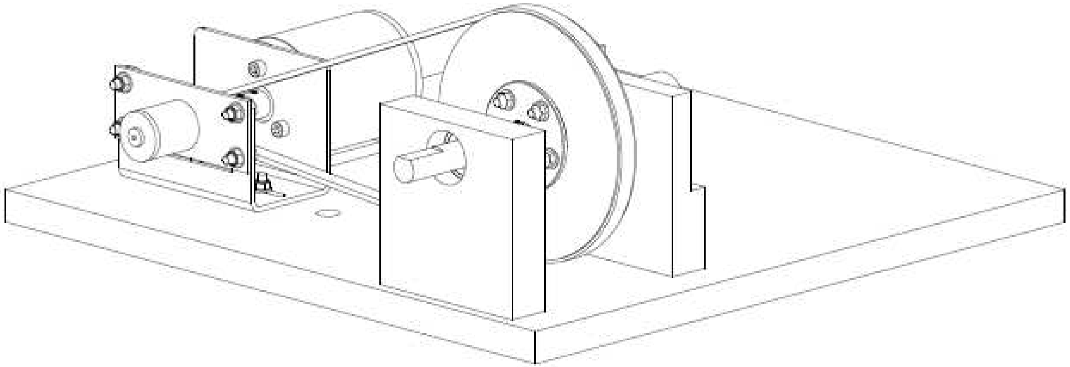


Figure 4.? Mechanical Assembly







ITEM NO.	PART	DWG No.	QTY.
1	Base Plate	GP-0110	1
2	Front Block	GP-0100	1
3	Rear Block	GP-0101	1
4	30x10x9 Bearing	-	2
5	Main Shaft	GP-0103	1
6	Collar	GP-0112	1
7	Timing Pulley Hub	GP-0104	1
8	Timing Pulley Washer	GP-0105	1
9	84T Timing Pulley T-5	GP-0109	1
10	M8 x 50 CSKCS	-	4
11	Potentiometer Mount	GP-0103	1
12	M5 x 30 CSKCS	-	2
13	M5 Washer	-	9
14	M5 Nut	-	7
15	Motor - Tacho Assembly	GA-0101	1
16	M5 Nylock	-	2
17	M5x20 SHCS	-	5
18	Servo Potentiometer	-	1
19	Rubber Block	-	1
20	M5 x 20 Dowel Pin	-	1
21	Steering Stop	GP-0111	1
22	Belt 750mm T-5	-	1
23	M5 x 5 FPSS	-	3
24	M5x10 SHCS	-	1
25	M3 x 3 FPSS	-	4
26	10mm External Circlip	-	1

CONTACT: GEOFF O'SHANNASSY
STUDENT#: Q1121004
PH: 0404 001 692

ALL DIMENSIONS ARE IN MILLIMETERS
TOLERANCES UNLESS SPECIFIED
X ± 1.0
XX ± 0.5
XXX ±0.05

DEBUR AND BREAK SHARP EDGES
SURFACE FINISH

DWG NO. **GA-0100**
MATERIAL:

FORCE FEED BACK WHEEL

A4

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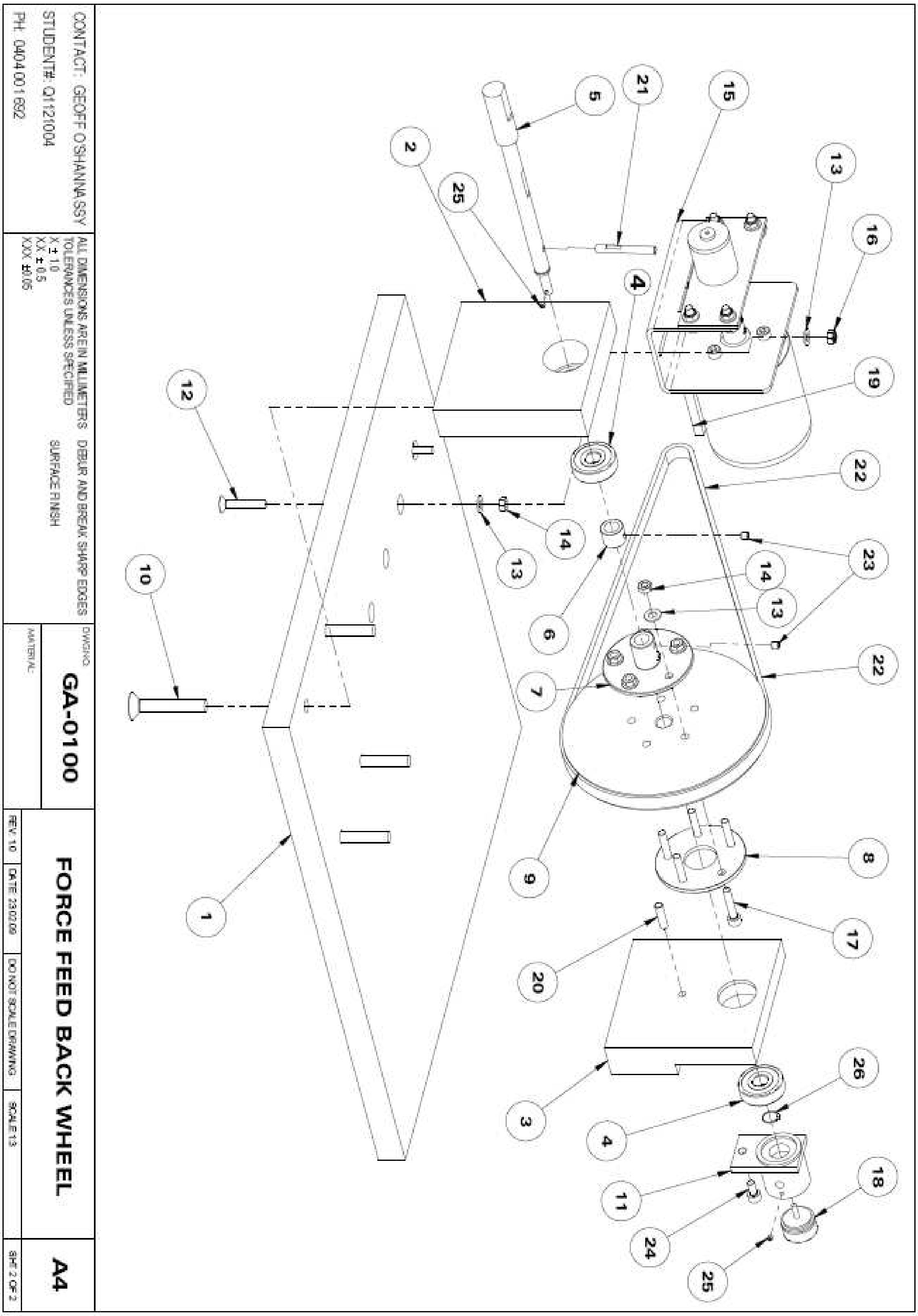
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XX ± 0.5
XXX ±0.05
SURFACE FINISH
DWG NO.
GA-0100
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REV 1.0
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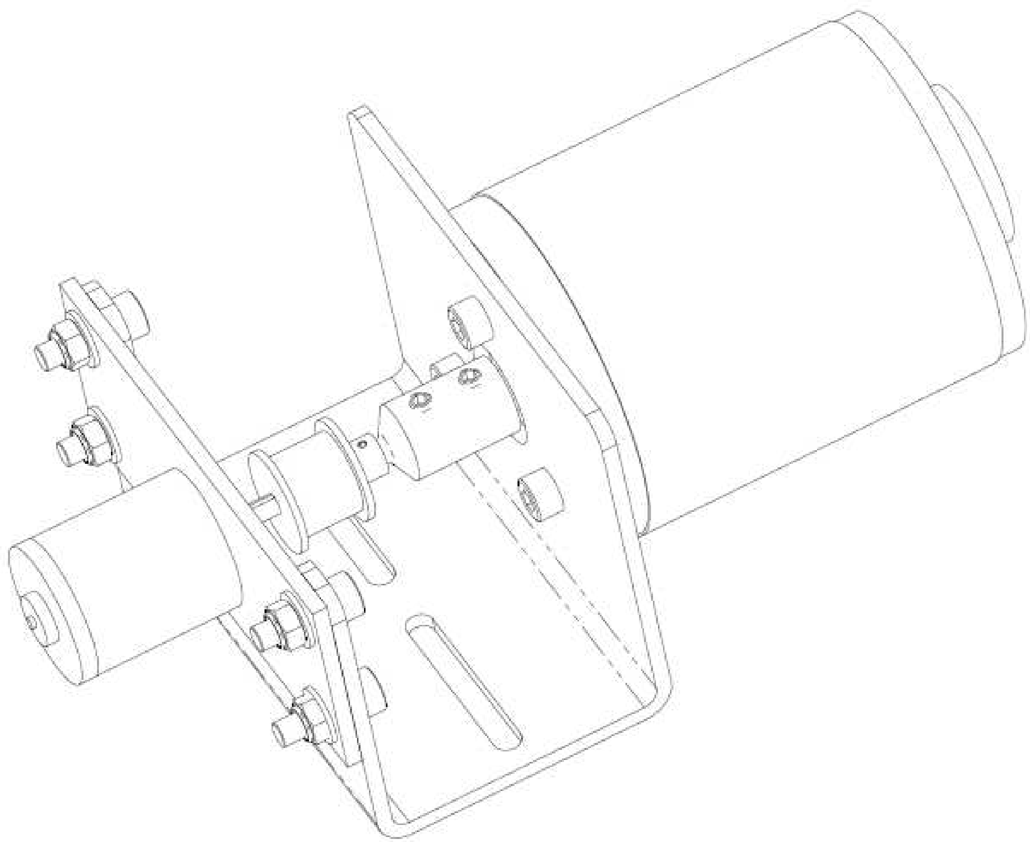
SHT 2 OF 2



ITEM NO.	PART	DWG No.	QTY.
1	Motor Bracket	GP-0106	1
2	100W Motor	-	1
3	Motor - Tacho Shaft	GP-0107	1
4	Tacho Motor		1
5	Rubber Mount	GP-0113	1
6	10T Timing Pulley T-5	GP-0108	1
7	M5 x 5 FPSS	-	2
8	M5x10 SHCS	-	3
9	M5x15 SHCS	-	4
10	M5 Washer	-	4
11	M5 Nylock	-	4
12	M2 x 2 FPSS	-	2

CONTACT: GEOFF O'SHANNASSY
STUDENT#: Q1121004
PH: 0404 001 692

ALL DIMENSIONS ARE IN MILLIMETERS
TOLERANCES UNLESS SPECIFIED
X ± 1.0
XX ± 0.5
XXX ±0.05

DEBUR AND BREAK SHARP EDGES
SURFACE FINISH

DWG NO. GA-0101
MATERIAL:

MOTOR - TACHO ASSEMBLY

A4

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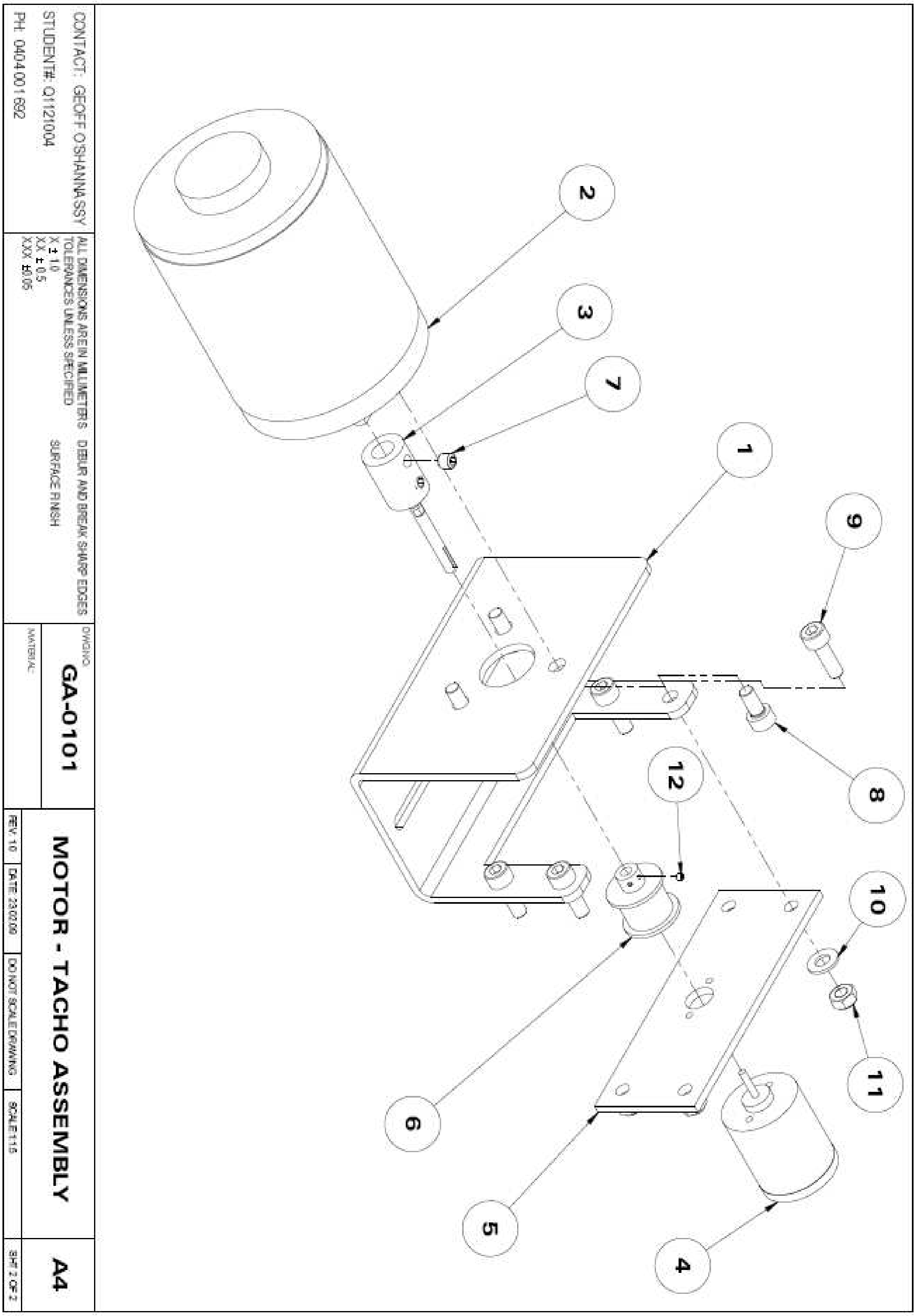

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DEBUR AND BREAK SHARP EDGES
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Appendix C Software Lisiting

Program listing for Position Control.Bas

```
Dim vel As Word  'current velocity reading
Dim veldemand As Word  'velocity demanded proportional to position
error
Dim velmax As Word  'maximum clockwise velocity
Dim velmin As Word  'maximum anti-clockwise veloctiy
Dim vel0 As Word  'velocity reading corresponding to stantionary
Dim velgain As Byte  'velocity error gain MAXIMUM VALUE 150

vel0 = 32000
velmax = vel0 + 5000
velmin = vel0 - 5000
velgain = 10


Dim pos As Word  'current position reading
Dim posdemand As Word  'usually centre position, but can be set for
active assistance mode
Dim posdemandr As Word
Dim posdemandl As Word
Dim posgain As Byte  'position error gain MAXIMUM VALUE 110
Dim gap As Byte  'sets the width of the deadzone
gap = 1
posdemand = 32000  'centre position
posdemand = 32000
posdemandl = posdemand - gap
posdemandr = posdemand + gap
posgain = 6

Dim mdrv As Word  'output to motor drive
Dim mdrvt As Word  'temporary motor dirve out to avoid dangerous
output
Dim mdrvmax As Word  'maximum clockwise motor drive - to limit torque
mdrv = 2048
Dim mdrvmin As Word  'maximum anti-clockwise motor drive - to limit
torque mdrv = 0
Dim mdrv0 As Word  'motordrive to 0 output. mdrv = 1100
```

```
mdrv = 1100  'motor stopped
mdrv0 = 32000
'mdrvmax = 32940  'CW drive saturation
'mdrvmin = 30900  'CCW drive saturation
mdrvmax = 33000  'mdrv0 + 500
mdrvmin = 31000  'mdrv0 - 500

Dim pulsehigh As Bit  'flag to control  and SEROUT

'timing variable declarations
Dim time19ms As Word
Dim time1ms As Word
Dim length As Word
Dim tlength As Word
Dim hightime As Word
Dim lowtime As Word

mdrv = mdrv0  'set motor drive to zero

'it is VERY IMPORTANT that timer 1 be initialized and started ASAP
'to ensure that a STOP motor drive signal is sent to the motor driver
board
Gosub initialize_timer1
Enable High

Gosub initialize
Gosub initialize_interrupt
Gosub initialize_adc

'** not implemented'set safety signal ok - circuit not yet configured
for this

'** not implemented Gosub calibrate 'commission at another time

'**********************************************************************
*********
'** MAIN PROGRAM


main:
      If pulsehigh = 1 Then Gosub senddata
      Goto main
```

```
End


'*********************************************************************
*********
'**  TIMER INITIALIZATION sUBROUTINE

initialize_timer1:
      'Timer as 1-2ms Pulse Every 15-20ms
      'T1CON - Timer 1 Control Register settings
      'RD16  =0  'ENABLE READ/WRITE OF Timer 1 IN ONE 16 BIT OPERATION
      'BIT 6 =0  UNUSED = 0
      'T1CKPS1:T1CKSP0 = 00  SET PRESCALER TO 1
      'T1OSCEN = 0 DISABLE OSCILLATOR
      'T1SYNC = 1 DO NOT SYNC EXTERNAL CLOCK
      'TMR1CS = 0 INTERNAL CLOCK (FOSC/4)
      'TMR1ON = 1 ENABLE TIMER
      '**  NOTE***  ONE CLOCK CYCLE = 400ns = 4/FOSC
      T1CON = 0x05  'set T0CON as above

      time1ms = 63035
      time19ms = 18035

      'times for use in simulator
      'also uncomment shiftright in mdrv routien
      'time1ms = 65285  'For 100us High base time
      'time19ms = 60785  'For 1.9ms Low base time

      TMR1L = 0xd0  'set an intial timer value of 15535
      TMR1H = 0xff  '50000 to overflow = 20ms
      IPR1.TMR1IP = True  'set timer 1 priority as high
      PIE1.TMR1IE = True  'enable timer 1 interrupt
      PIR1.TMR1IF = False  'clear timer 1 interrupt flag


Return

'*********************************************************************
*********
'**  INITIALIZATION sUBROUTINE

initialize:
      'gap = 10
```

```
        'posdemandr = 546  'posdemand + gap
        'posdemandl = 526  'posdemand - gap
        'set TRISC RC0 - RC7 as outputs
        TRISC = 0x00
        Hseropen 57600  'open serial port at 57600 bps
        'initialize serial port
        'velgain = 3  'MAXIMUM VELOCITY GAIN = 150
        'posgain = 30  'MAXIMUM POSITION GAIN = 110
        'mdrvmax = 2048  '100% CW drive at 2048
        'mdrvmin = 0  '100% CCW drive at 0
        Low pulsehigh
Return



'**********************************************************************
*********
'** INTERRUPT INITIALIZATION sUBROUTINE

initialize_interrupt:
        'note that interrups for timer 1 are set in the timer 1
intialization routine
        'set external interrupt int1
        INTCON2.INTEDG1 = False  'set int1 as falling edge
        INTCON3.INT1IP = True  'set int1 as high priority
        INTCON3.INT1IF = False  'clear int1 interrupt flag
        INTCON3.INT1IE = True  'enable int1 (RB0)
Return



'**********************************************************************
*********
'** ADC INITIALIZATION SUBROUTINE

initialize_adc:
        TRISA = 0x7f  'set all RA6-RA0 as inputs
        'ADCON1.ADFM  = 1  result is right justified
        'ADCON1.ADCS2 = ADC clock = FOSC/2
        'ADCON1.4-5 - unused 0
        'ADCON1. PCFG3-0 = 0000 'set ra0- ra7 to analogue inputs
        ADCON1 = 0x80
        'these two lines could possibly be removed
        Define ADC_CLOCK = 0
```

```
      Define ADC_SAMPLEUS = 0
Return



'***********************************************************************
*********
'** SEND DATA sUBROUTINE

senddata:
      'check TX send buffer flag here first
      Hserout #pos, " , ", #vel, " , ", #veldemand, " , ", #mdrv, CrLf
'remove #'s later
      Low pulsehigh
      Toggle PORTC.4
Return



'***********************************************************************
*********
'** POSTION CONTROL SUBROUTINE

calcmd:

'calulate velocity demand from position error
      If posdemandl > pos Then
            veldemand = vel0 + posgain * (posdemand - pos)
      Else
            If posdemandr < pos Then
                  veldemand = vel0 - posgain * (pos - posdemand)
            Else
                  veldemand = vel0
            Endif
      Endif

'limit velocity
      If veldemand > velmax Then
            veldemand = velmax
      Else
            If veldemand < velmin Then
                  veldemand = velmin
            Endif
      Endif
```

```
'calulate mdrv from velocity error
      If veldemand > vel Then
            mdrvt = mdrv0 + (velgain * (veldemand - vel)) / 29
      Else
            If veldemand < vel Then
                  mdrvt = mdrv0 - (velgain * (vel - veldemand)) / 29
            Else
                  mdrvt = mdrv0
            Endif
      Endif

'limit motordrive
'mdrvt = (mdrvt / 29) + 32000
      If mdrvt > mdrvmax Then
            mdrvt = mdrvmax
      Else
            If mdrvt < mdrvmin Then
                  mdrvt = mdrvmin
            Endif
      Endif
      'mdrv = mdrvt / 29
      mdrv = mdrvt - 30900


Return


'***********************************************************************
*********
'** MDRVOUT sUBROUTINE
mdrvout:
      'sends the 1-2ms pulse to the motor driver board. RB2 pin
      If PORTC.5 = 0 Then
            Adcin 0, vel
            vel = (vel * 20) + 24640
            Adcin 1, pos
            pos = pos + 31488
            Gosub calcmd

'NOTE this line only for testing
'mdrv = ShiftRight(mdrv, 3)  'divide by 8
```

```
            High PORTC.5  'Set PORTC.5 high
            'set high time
            hightime = time1ms - mdrv  '63035 = 1ms to overflow
            lowtime = time19ms + mdrv  '18035 = 19ms to overflow
            TMR1L = hightime.LB
            TMR1H = hightime.HB
            High pulsehigh

      Else
            Low PORTC.5  'set PORTC.5 low
            'set low time
            TMR1L = lowtime.LB
            TMR1H = lowtime.HB
      Endif
Return

On High Interrupt
      Gosub mdrvout

      'check rb0 int0 first - safety relay tripped input
      'hardware error condition stop execution until resolved
      PIR1.TMR1IF = 0  'RESET INTERRUPT FLAG
Resume

On Low Interrupt
      'not yet implemented
Resume
```

Program listing for STrace.vb

```
Imports System.Drawing
Imports Microsoft.VisualBasic.PowerPacks
Imports System.Math

Public Class STrace
    Dim screensize As Size
    Dim Xcen As Decimal
    Dim Ycen As Decimal
    Dim signal1 As Decimal
    Dim signal2 As Decimal
    Dim signal3 As Decimal
    Dim signal4 As Decimal
    Dim psignal1 As Decimal
    Dim psignal2 As Decimal
    Dim psignal3 As Decimal
    Dim psignal4 As Decimal
```

```
    Dim t As Decimal
    Dim dt As Decimal
    Dim sdata As String

    Dim plott As Decimal
    Dim prevT As Decimal
    Dim maxy As Decimal
    Dim tracewidth As Decimal
    Dim plotting As Boolean
    Private MyImage As Bitmap
    Private MyGraphic As Graphics
    Private Sub Form1_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        Me.ResizeRedraw = True
        Me.SetStyle(ControlStyles.AllPaintingInWmPaint, True)
        Me.DoubleBuffered = True
        Me.SetStyle(ControlStyles.OptimizedDoubleBuffer, True)
        screensize = Me.Size
        Xcen = PictureBox1.Width / 2
        Ycen = PictureBox1.Height / 2
        MyImage = New Bitmap(PictureBox1.Width, PictureBox1.Height)
        MyGraphic = Graphics.FromImage(MyImage)

        'start timer 1
        Timer1.Enabled = True

        plotting = False
        tracewidth = 8000
        TextBox1.Text = Convert.ToString(tracewidth / 1000) + " s"
        sdata = "0,0,0,0"
        getsignal()
        SerialPort1.Open()
    End Sub

    Private Sub Timer1_Tick(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Timer1.Tick
        'getsignal()
    End Sub

    Private Sub getsignal()
        Dim temp() As String
        'Label1.Text = sdata
        temp = sdata.Split(",")
        signal1 = (Convert.ToInt64(temp(0)) - 32000) / 482 * 300 '*
PictureBox1.Height / 1024
        signal2 = (Convert.ToInt64(temp(1)) - 32000) / 4000 * 300 '*
PictureBox1.Height / 1024
        'signal3 = (Convert.ToInt64(temp(2)) - 32000) '*
PictureBox1.Height / 1024
        'signal4 = (Convert.ToInt64(temp(3)) - 1100) '*
PictureBox1.Height / 1024
        'signal1 = Math.Cos(t / 1000) * 120
        'signal2 = Math.Sin(t / 1000) * 200
        'signal3 = t / 10
    End Sub

    Private Sub PlotTrace()
        Dim path As New Drawing2D.GraphicsPath
        Dim gridcolour As Color = System.Drawing.Color.FromArgb(255,
0, 35, 0)
        Dim brightgreen As Color = System.Drawing.Color.FromArgb(255,
0, 255, 0)
        Dim gridpen As New Pen(gridcolour)
        Dim BgreenPen As New Pen(brightgreen)
```

```
        Dim time As New Stopwatch()
        Dim xgrid As Decimal
        Dim ygrid As Decimal
        time.Start()
        'gridpen.DashStyle = Drawing2D.DashStyle.Dash
        prevT = 0


        'MyGraphic.SmoothingMode = Drawing2D.SmoothingMode.AntiAlias

        While plotting
            'eraser.Width = (tracewidth * 0.001) + 20
            t = time.ElapsedMilliseconds
            'getsignal()
            If t > tracewidth Then
                time.Reset()
                t = 0
                time.Start()
                MyGraphic.FillRectangle(Brushes.Black, 0, 0, 20,
PictureBox1.Height)
                prevT = 0
            End If
            plott = PictureBox1.Width * t / tracewidth

            MyGraphic.FillRectangle(Brushes.Black, plott, 0, 20,
PictureBox1.Height)

            'gridpen.ResetTransform()
            'gridpen.ScaleTransform(10, 1)
            'For ygrid = 0 To PictureBox1.Height Step 50
            'MyGraphic.DrawLine(gridpen, 0, ygrid, PictureBox1.Width,
ygrid)
            'Next
            'gridpen.ResetTransform()
            'gridpen.ScaleTransform(1, 50)
            'For xgrid = 0 To PictureBox1.Width Step 50
            ' MyGraphic.DrawLine(gridpen, xgrid, 0, xgrid,
PictureBox1.Height)
            'Next


            MyGraphic.DrawLine(Pens.DarkGreen, 0, Ycen,
PictureBox1.Width, Ycen)

            MyGraphic.DrawLine(BgreenPen, prevT, Ycen - psignal1,
plott, Ycen - signal1)
            MyGraphic.DrawLine(Pens.Blue, prevT, Ycen - psignal2,
plott, Ycen - signal2)
            MyGraphic.DrawLine(Pens.Red, prevT, Ycen - psignal3,
plott, Ycen - signal3)
            MyGraphic.DrawLine(Pens.Yellow, prevT, Ycen - psignal4,
plott, Ycen - signal4)


            PictureBox1.Image = MyImage
            prevT = plott
            psignal1 = signal1
            psignal2 = signal2
            psignal3 = signal3
            psignal4 = signal4

            Signal1box.Text = Convert.ToString(signal1)
            Signal2Box.Text = Convert.ToString(signal2)
            Signal3box.Text = Convert.ToString(signal3)
```

```
            Signal4box.Text = Convert.ToString(signal4)

            System.Windows.Forms.Application.DoEvents()
        End While

    End Sub

    Private Sub StartButton_Click(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles StartButton.Click
        plotting = True
        PlotTrace()

    End Sub

    Private Sub PauseButton_Click(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles PauseButton.Click
        plotting = False
    End Sub

    Private Sub TrackBar1_Scroll(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles TrackBar1.Scroll
        tracewidth = (TrackBar1.Value \ 100) * 100
        TextBox1.Text = Convert.ToString(tracewidth / 1000) + " s"

    End Sub

    Private Sub SerialPort1_DataReceived(ByVal sender As Object, ByVal
e As System.IO.Ports.SerialDataReceivedEventArgs) Handles
SerialPort1.DataReceived
        sdata = SerialPort1.ReadLine()
        getsignal()
    End Sub
End Class
```

Program listing for BMApp.vb

```
Imports Microsoft.VisualBasic.PowerPacks
Imports System.Math
Imports System.IO.Ports
Imports System.Drawing

Public Class Form1
    'declare program variables here
    Dim screensize As Size
    Dim relative = False
    Dim grid = False
    Dim tval = 0
    Dim Xcen As Integer
    Dim Ycen As Integer
    Dim Xpos As Integer
    Dim Xmove As Integer
    Dim Offset As Integer
    Dim prevmove As Integer
    Dim trackcounter As Integer
    Dim trackoffset As Single = 0
    Dim trackwidth As Integer = 200
    Dim carpos As Integer = 400
    Dim trackBM = New Bitmap(My.Resources.trackedge)
    Dim car = New Bitmap(My.Resources.car)

    Dim road = New Bitmap(My.Resources.road)
```

```
    'Dim trackbrush(3) As TextureBrush
    Dim trackbrush = New TextureBrush(trackBM, New RectangleF(0, 0,
10, 80))

    Dim roadbrush = New TextureBrush(road)
    Dim roadoffset As Integer = 0

    'Dim trackBM As Bitmap
    Dim trackpen As New Pen(Color.White, 10)

    Dim findedge As Color
    'Dim trackbrush = New TextureBrush(trackBM)


    Dim ypos As Integer
    Dim ptsr(7) As PointF
    Dim ptsl(7) As PointF
    Dim track() As Decimal = New Decimal() {400, 400, 400, 400, 400,
400, 400, 350, 300, 350, 330, 300, 360, 400, 450, 470, 410, 410, 400,
360, 355, 350, 400, 400, 400, 400, 400, 400}
    Private MyImage As Bitmap
    Private MyGraphic As Graphics


    Private Sub Form1_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        If SPort.IsOpen Then
            SPort.Close()
        End If
        SPort.Open()

        '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
        Xcen = PictureBox1.Width / 2
        Ycen = PictureBox1.Height / 2
        MyImage = New Bitmap(PictureBox1.Width, PictureBox1.Height)
        MyGraphic = Graphics.FromImage(MyImage)

        car.MakeTransparent(Color.White)

        Xmove = 1
        Xpos = Xcen
        trackcounter = 0
        TrackLabel.Text = Convert.ToString(trackcounter)
        trackpen.Brush = trackbrush
    End Sub

    Private Sub GraphicsApp_Paint(ByVal sender As Object, ByVal e As
System.Windows.Forms.PaintEventArgs) Handles Me.Paint

    End Sub

    Private Sub Timer1_Tick(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Timer1.Tick
        Dim path As New Drawing2D.GraphicsPath

        If trackoffset > 39 Then
            trackoffset = 0
            trackbrush.ResetTransform()
```

```
        End If
        trackoffset += 2
        If roadoffset > 512 Then
            roadoffset = 0
            roadbrush.ResetTransform()
        End If
        roadoffset += 2

        trackbrush.TranslateTransform(0, 2)
        roadbrush.TranslateTransform(0, 2)
        trackpen.Brush = trackbrush
        MyGraphic.Clear(Color.Green)
        MyGraphic.SmoothingMode = Drawing2D.SmoothingMode.AntiAlias

        draw_track()
        path.AddCurve(ptsl)
        path.AddLine(ptsl(7).X, ptsl(7).Y, ptsr(0).X, ptsr(0).Y)
        path.AddCurve(ptsr)
        path.AddLine(ptsr(7).X, ptsr(7).Y, ptsl(0).X, ptsl(0).Y)


        MyGraphic.FillPath(Brushes.Gray, path)
        MyGraphic.DrawPath(trackpen, path)

        MyGraphic.DrawImage(car, carpos, 540)

        'Display the image to the screen
        PictureBox1.Image = MyImage

    End Sub

    Private Sub draw_track()
        Dim pcounter As Integer
        Dim maxcount As Integer
        maxcount = track.Length
        'path.ClearMarkers()
        If Offset = 200 Then
            Offset = 0
            trackcounter += 1
            TrackLabel.Text = Convert.ToString(trackcounter)
        End If
        If trackcounter > (maxcount - 8) Then
            trackcounter = 0
        End If

        ypos = 1000
        For pcounter = 0 To 7
            ptsl(pcounter).X = track(trackcounter + pcounter) -
trackwidth / 2
            ptsl(pcounter).Y = ypos + Offset
            ypos -= 200
        Next
        ypos += 200
        For pcounter = 0 To 7
            ptsr(pcounter).X = track(trackcounter + 7 - pcounter) +
trackwidth / 2
            ptsr(pcounter).Y = ypos + Offset
            ypos += 200
        Next
        'ptsl(0).X = track(0)
        'ptsl(0).Y = 800 + Offset
        'ptsl(1).X = track(1)
        'ptsl(1).Y = 600 + Offset
        'ptsl(2).X = track(2)
```

```
        'ptsl(2).Y = 400 + Offset
        'ptsl(3).X = track(3)
        'ptsl(3).Y = 200 + Offset
        'ptsl(4).X = track(4)
        'ptsl(4).Y = 0 + Offset
        'ptsl(5).X = track(5)
        'ptsl(5).Y = -200 + Offset
        'path.AddCurve(ptsl)

        Offset += 5


    End Sub

    Private Sub PauseButton_Click(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles PauseButton.Click
        If Timer1.Enabled = True Then
            Timer1.Enabled = False
        Else
            Timer1.Enabled = True
        End If
    End Sub


    Private Sub SPort_DataReceived(ByVal sender As Object, ByVal e As
System.IO.Ports.SerialDataReceivedEventArgs) Handles
SPort.DataReceived
        Dim sdata As String
        Dim tempstring() As String
        sdata = SPort.ReadLine()
        tempstring = sdata.Split(" ")
        carpos = Convert.ToInt16(tempstring(0))
    End Sub
End Class
```

SN54LS21, SN74LS21
DUAL 4-INPUT POSITIVE-AND GATES

SDLS139 – APRIL 1985 – REVISED MARCH 1988

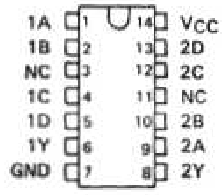
- Package Options Include Plastic "Small Outline" Packages, Ceramic Chip Carriers and Flat Packages, and Plastic and Ceramic DIPs
- Dependable Texas Instruments Quality and Reliability

description

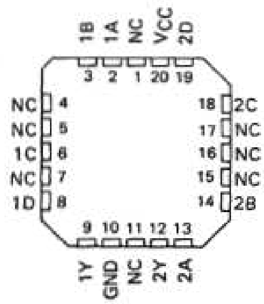
These devices contain two independent 4-input AND gates.

The SN54LS21 is characterized for operation over the full military temperature range of −55°C to 125°C. The SN74LS21 is characterized for operation from 0°C to 70°C.

SN54LS21 . . . J OR W PACKAGE
SN74LS21 . . . D OR N PACKAGE
(TOP VIEW)



SN54LS21 . . . FK PACKAGE
(TOP VIEW)

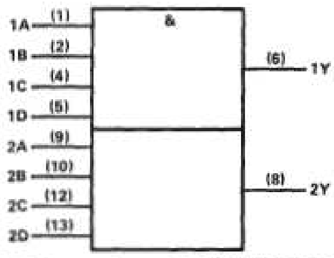


NC – No internal connection

FUNCTION TABLE (each gate)

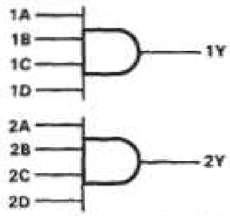
INPUTS				OUTPUT
A	B	C	D	Y
H	H	H	H	H
L	X	X	X	L
X	L	X	X	L
X	X	L	X	L
X	X	X	L	L

logic symbol†



† This symbol is in accordance with ANSI/IEEE Std 91-1984 and IEC Publication 617-12.
Pin numbers shown are for D, J, N, and W packages.

logic diagram



(positive logic) $Y = A \cdot B \cdot C \cdot D$ or $Y = \overline{\overline{A} + \overline{B} + \overline{C} + \overline{D}}$

TEXAS INSTRUMENTS
POST OFFICE BOX 655303 ● DALLAS, TEXAS 75265

FAIRCHILD
SEMICONDUCTOR™

August 1986
Revised March 2000

DM74LS112A
Dual Negative-Edge-Triggered Master-Slave J-K Flip-Flop with Preset, Clear, and Complementary Outputs

General Description

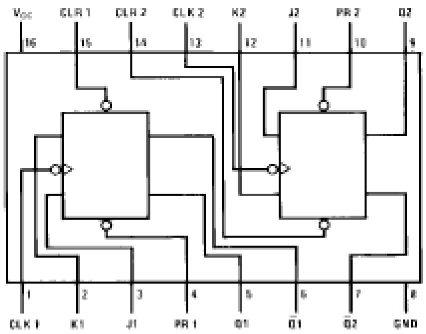
This device contains two independent negative-edge-triggered J-K flip-flops with complementary outputs. The J and K data is processed by the flip-flop on the falling edge of the clock pulse. The clock triggering occurs at a voltage level and is not directly related to the transition time of the falling edge of the clock pulse. Data on the J and K inputs may be changed while the clock is HIGH or LOW without affecting the outputs as long as the setup and hold times are not violated. A low logic level on the preset or clear inputs will set or reset the outputs regardless of the logic levels of the other inputs.

Ordering Code:

Order Number	Package Number	Package Description
DM74KS112AM	M16A	16-Lead Small Outline Integrated Circuit (SOIC), JEDEC MS-012, 0.150 Narrow
DM74LS112AN	N16E	16-Lead Plastic Dual-In-Line Package (PDIP), JEDEC MS-001, 0.300 Wide

Devices also available in Tape and Reel. Specify by appending the suffix letter "X" to the ordering code.

Connection Diagram



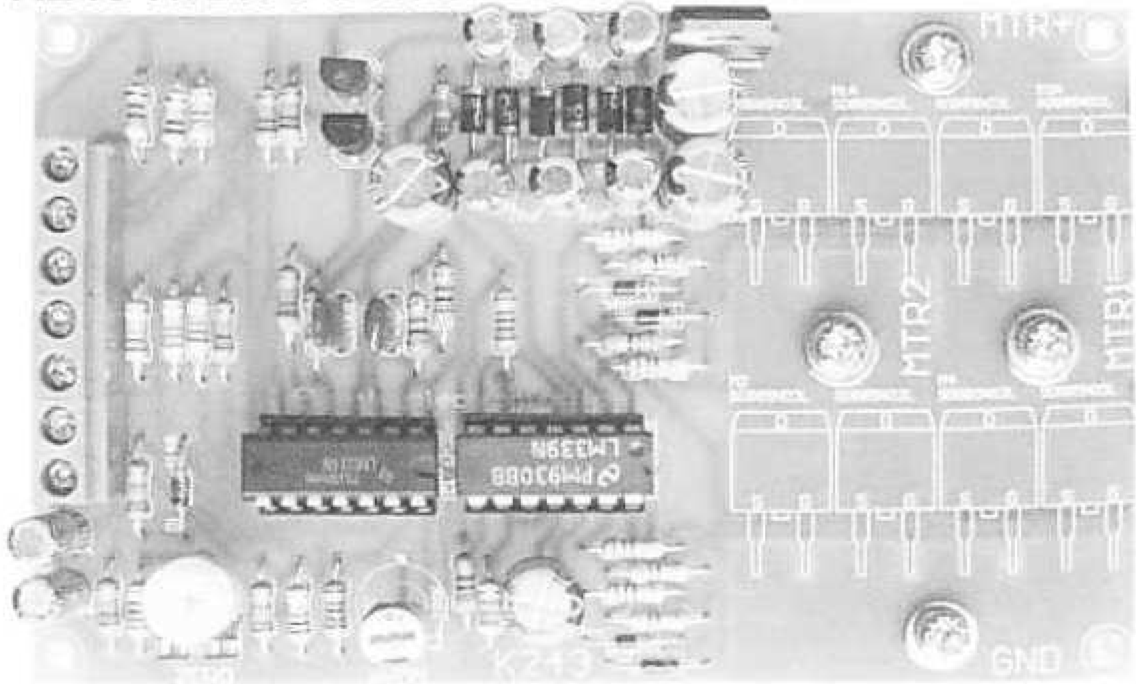
Function Table

Inputs					Outputs	
PR	CLR	CLK	J	K	Q	$\overline{Q}$
L	H	X	X	X	H	L
H	L	X	X	X	L	H
L	L	X	X	X	H (Note 1)	H (Note 1)
H	H	↓	L	L	Q_0	$\overline{Q}_0$
H	H	↓	H	L	H	L
H	H	↓	L	H	L	H
H	H	↓	H	H	Toggle	
H	H	H	X	X	Q_0	$\overline{Q}_0$

H = HIGH Logic Level
L = LOW Logic Level
X = Either LOW or HIGH Logic Level
↓ = Negative Going Edge of Pulse
Q_0 = The output logic level before the indicated input conditions were established.
Toggle = Each output changes to the complement of its previous level on each falling edge of the clock pulse.

Note 1: This configuration is nonstable; that is, it will not persist when preset and/or clear inputs return to their inactive (HIGH) level.

K243 HIGH POWER DC SPEED CONTROLLER

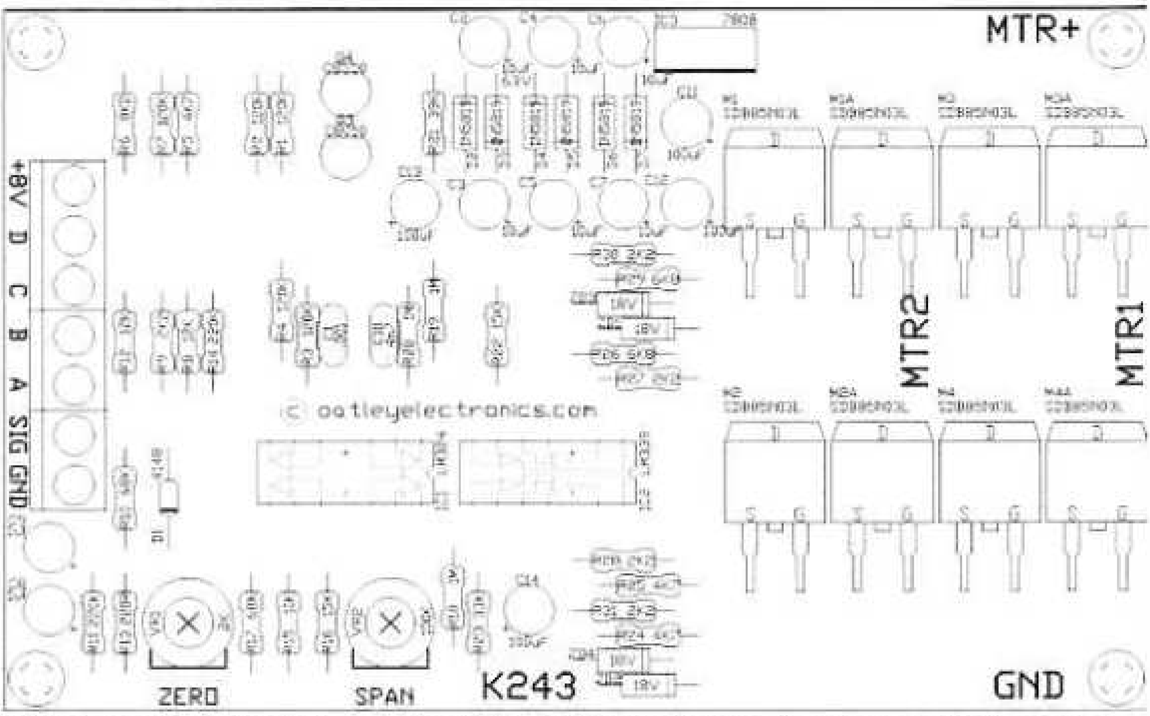


NOTE: Make sure you read and understand these notes fully before starting construction.

This reversible DC motor speed controller can be controlled by a single potentiometer or a 1-2mS pulse from standard R/C hobby remote controls that control standard servos. This kit features a bridge driver that employs 80A "N-Channel" MOSFETs that have an on resistance of 5 milliohms, and are suitable for 10-30V operation. When tested with a loaded 24V motor at a continuous 10 Amperes the MOSFETs got slightly warm. No additional heatsinking would be required for operation at 20A. This test was conducted with just 4 MOSFETs in the output bridge, but there is provision for another 4 optional MOSFETs to be paralleled with the existing ones in the output bridge driver. Adding an extra device in parallel with an existing one would result in each of the paralleled MOSFETs having ¼ of the power dissipation when compared to the original single device! In a 24V system there would be no problem powering motors with a power rating of up to 1KW.

CONSTRUCTION
Construction is simple and best started with the SDB85N03L surface mount MOSFETs. Solder the legs of the MOSFETs first and then solder the metal tag of each MOSFET to the PCB. A clothes peg may be useful to hold the MOSFETs in place while soldering them. It is important to place them in the correct location so as to leave room for the additional MOSFETs if you fit them.

CIRCUIT DESCRIPTION:
An interesting feature of this circuit is the use of 4 identical "N" channel MOSFETs in the output bridge. In order to switch on the two top MOSFETs they require a gate voltage that is higher than the main (motor) supply voltage. Operational amplifier IC1:A and its associated components form a square wave oscillator which operates at around 4KHz and produces an output voltage of 6V P-P. Transistors Q3 and Q4 are configured as emitter followers and the combination produces an output voltage of 4.8V P-P. This AC output voltage is used to drive a voltage multiplier made up of diodes D2-D7 and capacitors C2-C7. The DC output voltage from this multiplier is approx. 15V higher than the main supply voltage. Note that IC2 (LM339) is a quad voltage comparator with an open circuit collector output. Its outputs are tied via resistors to either the main V+ or V++.
For the following explanation assume that a 10Kohm potentiometer is connected to terminals B, C, & D and that the trim-pot is initially centered. IC1:D and its associated parts form an oscillator with a saw-tooth output voltage of 1.2V P-P, whose low and high peak voltages are at 3.1V and 4.3V respectively. This sawtooth



voltage is applied to the non inverting input (+) of IC2:A and the inverting input (-) of IC2:B. Resistors R24, R25, and R26 form a voltage divider from the regulated +8V supply in order to bias the - input of IC2:A at 4.4V and the - input of IC2:B at 3V. Since the highest voltage at the + input of IC2:A is lower than the voltage at its input, its output is at "0". Also since the lowest input of IC2:B is higher than the voltage at its (+) input, its output is at "0". With the trim-pot centered the voltage at its viper (terminal C) is 4.2V. Note that this voltage is buffered by a voltage follower IC1:C and applied to the oscillator via R19. This buffer is not necessary but was included to use up a surplus operational amplifier. In the future we will make use of this operational amplifier to perform the function of Q1 and Q2, thus somewhat reducing the component count. Rotating the potentiometer so as the voltage at its viper becomes higher would offset the triangular wave DC component and cause it to rise. The output of IC2:A would go to a "1" for the portion of the triangular wave that rises above 4.4V. During this period MOSFET M1 would be turned on via R31. Since the + input of IC2:C is at a higher voltage than its input the output of the IC is at "1": In this case since its output is at V++ MOSFET Q3 would be turned on via R32. Rotating the potentiometer in order to make the offset voltage even higher would result in an increased conduction angle and when the bottom tips of the triangular wave are above 4.4V MOSFETs M1 and M3 would be turned on continuously.

In a similar explanation rotating the potentiometer from its centre positions so that the offset voltage becomes more negative would cause MOSFETs M4 and M1 to conduct and so result in a reverse polarity being applied to the motor, etc.

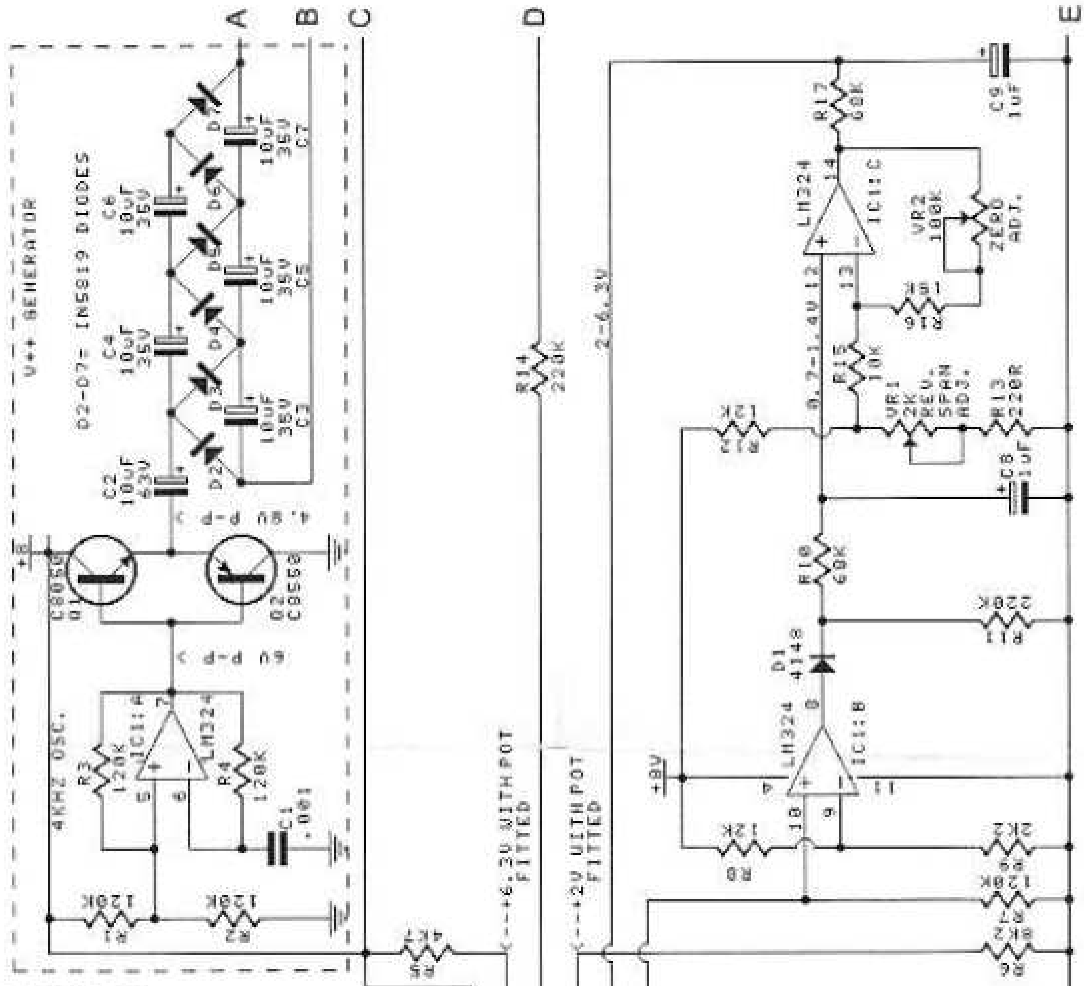
1-2mS (Radio Control) INPUT

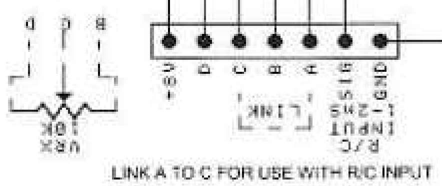
The 1-2mS input is designed for standard R/C equipment, It simply converts the 1-2mS input to an analogue voltage. It allows you to vari the speed of your motor throu the movement of your R/C transmitter's joystick. The 1-2mS input should be connected to the terminals marked "GND" and "SIG". The analogue output is available at the terminal marked "A" and needs to be linked to the terminal marked "C" if the R/C input is used. Note: The external pot must not be connected if you are using the R/C input. VR1 & VR2 are only to adjustment the 1-2mS (Radio Control) input if used.

CONNECTION

The screws and washers supplied in the kit can be used to connect to "Eye Terminals" as shown in the pictures accompanying these notes. For use with the R/C input, link terminal A with terminal C and leave out VRX 10K pot.

NOTE:
THE BATTERY AND POLARITY IS CRUCIAL!!!
REVERSE POLARITY MAY DESTROY THE KIT!!!





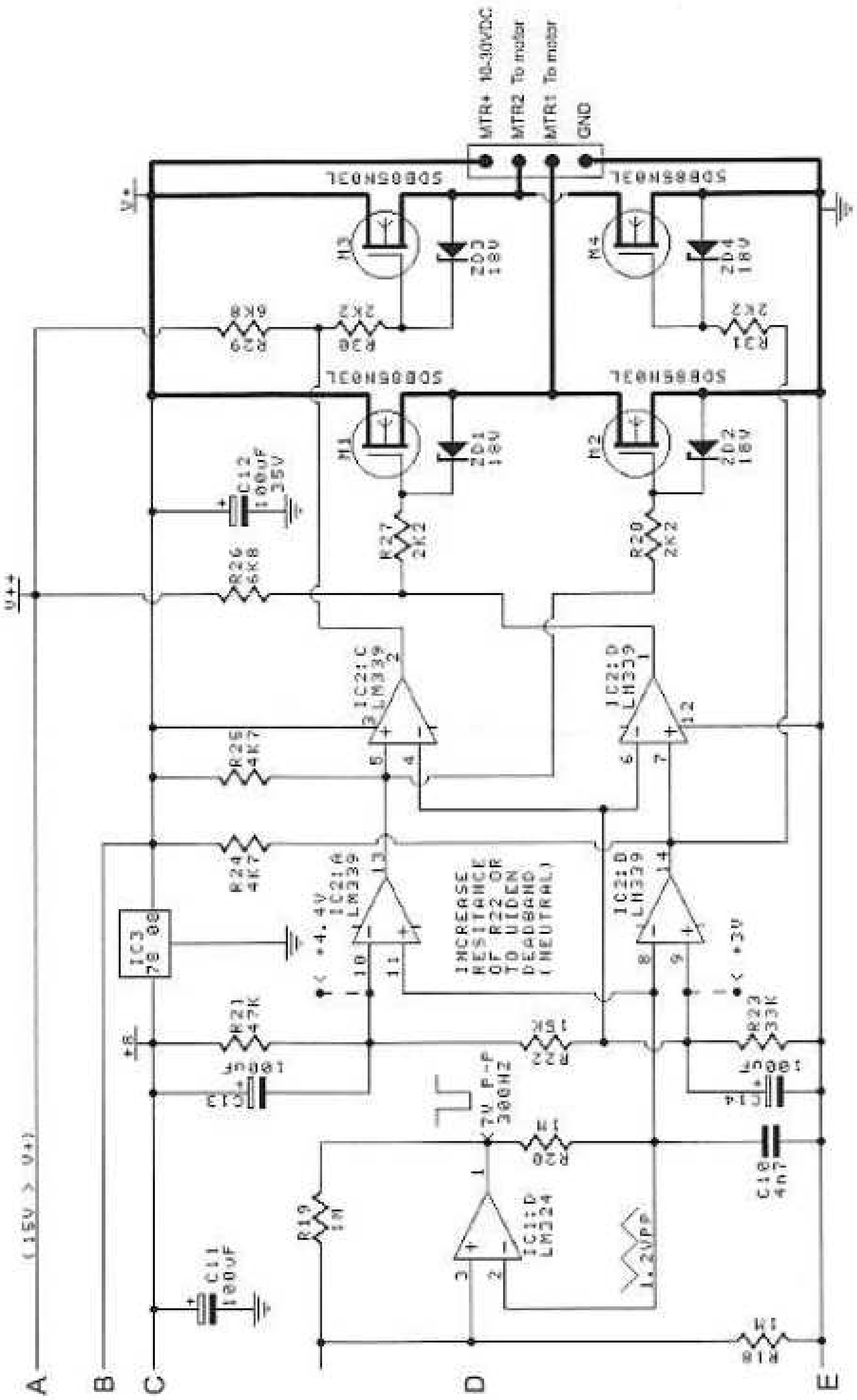
PARTS LIST

1 PCB coded OE-K243
4 3mm Screws
4 3mm Nuts
8 3mm Washers
2 14pin IC Sockets
1 2Kohm Trimpot
1 100 Kohm Trimpot
2 3way 5mm Screw Terminals

Semiconductors
1 LM339/uPC339 Quad Comparator IC
1 LM324 Quad Op-Amp IC
1 7808 Voltage Regulator IC
1 C8550 PNP Transistors
3 C8050 NPN Transistors
1 1N4148 Signal Diode
4 18V 400mW Zener Diodes
6 1N5819 Schottky Diodes
4 SDB85N03L N channel MOSFET's

Capacitors
1 1n polyester
1 4n7 polyester
2 1uF 16V electrolytic
5 10uF 35V electrolytic
4 100uF 35V electrolytic
4 100uF 63V electrolytic

Resistors (0.25W 5%)
1 220ohm
5 2K2ohm
3 4K7ohm
2 6K8ohm
1 8K2ohm
1 10Kohm
2 12Kohm
2 15Kohm
1 33Kohm
1 39Kohm
2 47Kohm
2 68Kohm
5 120Kohm
2 220Kohm
3 1Mohm


MTR+ 10-30VDC
MTR2 To motor
MTR1 To motor
GND
INCREASE RESITANCE OF R22 OR TO WIDEN DEADBAND (NEUTRAL)
A
B
C
D
E

National Semiconductor

December 1994

LM124/LM224/LM324/LM2902 Low Power Quad Operational Amplifiers

General Description

The LM124 series consists of four independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage.

Application areas include transducer amplifiers, DC gain blocks and all the conventional op amp circuits which now can be more easily implemented in single power supply systems. For example, the LM124 series can be directly operated off of the standard +5V power supply voltage which is used in digital systems and will easily provide the required interface electronics without requiring the additional ±15V power supplies.

Unique Characteristics

- In the linear mode the input common-mode voltage range includes ground and the output voltage can also swing to ground, even though operated from only a single power supply voltage
- The unity gain cross frequency is temperature compensated
- The input bias current is also temperature compensated

Advantages

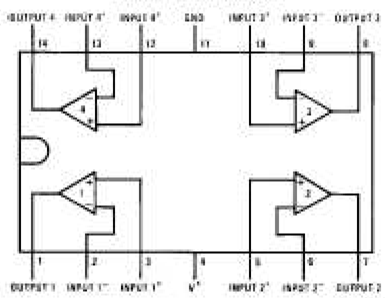
- Eliminates need for dual supplies
- Four internally compensated op amps in a single package
- Allows directly sensing near GND and V_{OUT} also goes to GND
- Compatible with all forms of logic
- Power drain suitable for battery operation

Features

- Internally frequency compensated for unity gain
- Large DC voltage gain 100 dB
- Wide bandwidth (unity gain) 1 MHz (temperature compensated)
- Wide power supply range:
  - Single supply 3V to 32V
  - or dual supplies ±1.5V to ±16V
- Very low supply current drain (700 μA)—essentially independent of supply voltage
- Low input biasing current 45 nA (temperature compensated)
- Low input offset voltage 2 mV and offset current 5 nA
- Input common-mode voltage range includes ground
- Differential input voltage range equal to the power supply voltage
- Large output voltage swing 0V to V+ − 1.5V

Connection Diagram

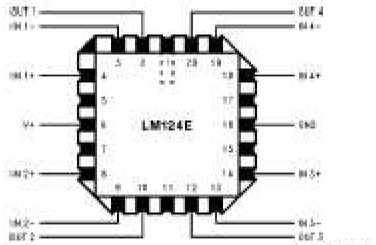
Dual-In-Line Package



TL/H/9299–1

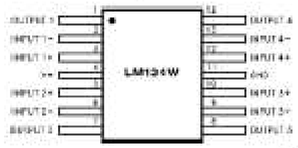
Top View

Order Number LM124J, LM124AJ, LM124J/883, LM124AJ/883*, LM224J, LM224AJ, LM324J, LM324M, LM324AM, LM2902M, LM324N, LM324AN or LM2902N**
See NS Package Number J14A, M14A or N14A



TL/H/9299–32

Order Number LM124AE/883 or LM124E/883
See NS Package Number E20A



TL/H/9299–33

Order Number LM124AW/883 or LM124W/883
See NS Package Number W14B

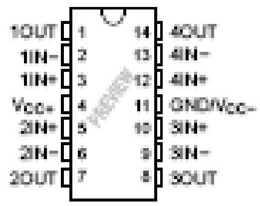
*LM124A available per JM38510/11006
**LM124 available per JM38510/11005

 RRD-B30M115/Printed in U. S. A.

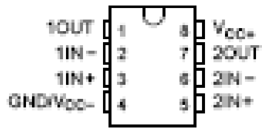
FEATURES

- 2.5-V, 2.7-V, and 5-V Performance
- –40°C to 125°C Operation
- No Crossover Distortion
- Low Supply Current at V_{CC+} = 5 V:
  - LMV821...0.3 mA Typ
  - LMV822...0.5 mA Typ
  - LMV824...1 mA Typ
- Rail-to-Rail Output Swing
- Gain Bandwidth of 5.5 MHz Typ at 5 V
- Slew Rate of 1.9 V/µs Typ at 5 V

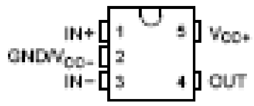
LMV824 . . . D, DGV, OR PW PACKAGE
(TOP VIEW)



LMV822 . . . D OR DGK PACKAGE
(TOP VIEW)



LMV821 . . . DBV OR DCK PACKAGE
(TOP VIEW)



DESCRIPTION/ORDERING INFORMATION

The LMV821 single, LMV822 dual, and LMV824 quad devices are low-voltage (2.5 V to 5.5 V), low-power commodity operational amplifiers. Electrical characteristics are very similar to the LMV3xx operational amplifiers (low supply current, rail-to-rail outputs, input common-mode range that includes ground). However, the LMV8xx devices offer a higher bandwidth (5.5 MHz typical) and faster slew rate (1.9 V/µs typical).

The LMV8xx devices are cost-effective solutions for applications requiring low-voltage/low-power operation and space-saving considerations. The LMV821 is available in the ultra-small DCK package, which is approximately half the size of SOT-23-5. The DCK package saves space on printed circuit boards and enables the design of small portable electronic devices (cordless and cellular phones, laptops, PDAs, PCMIA). It also allows the designer to place the device closer to the signal source to reduce noise pickup and increase signal integrity.

The LMV8xx devices are characterized for operation from −40°C to 85°C. The LMV8xxI devices are characterized for operation from −40°C to 125°C.

Model 157

Vishay Spectrol

Precision Industrial Potentiometer

FEATURES

- High Quality
- Short Length Behind Panel (11/32")
- Rugged One Piece Metal Housing
- Stainless Steel Shaft
- Long Rotational Life
- Wide Operating Temperature Range
- Linearities to ± 0.25% Special
- Optional Sealed Construction (Bushing Mount Only)

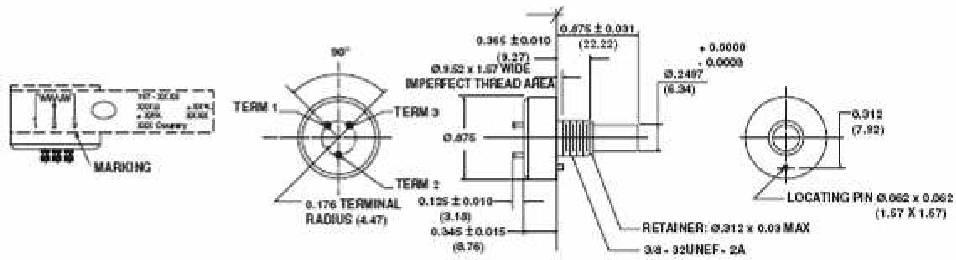
ELECTRICAL SPECIFICATIONS	
PARAMETER	MIL-PRF-39024 TEST PROCEDURES APPLY
Resistance	1KΩ to 100
Resistance Tolerance Special to	± 20% ± 10%
Linearity Special to	± 2.0% ± 0.25%
Temperature Coefficient of Resistance	± 600ppm/°C
Power Rating Derate to	1.0 watts at 40°C Ambient 0 watts at 125°C
Rotation	340° ± 4°
End Voltage	0.5% maximum
Dielectric Withstanding	1,000V_{RMS}, 60Hz
Insulation Resistance	100MΩ minimum, 500VDC
Output Smoothness	0.1%

MECHANICAL SPECIFICATIONS		
PARAMETER		
Weight	0.5 oz maximum	
Rotation	360° (Continuous)	
Mount Bearing Type	BUSHING Sleeve Bearing	SERVO Ball Bearing
Operating Torque Starting Running	 0.30 oz - in 0.25 oz - in	 0.25 oz - in 0.15 oz - in
Mechanical Tolerance (in/mm) (maximum) Shaft Runout (TIR) Pilot Dia Runout (TIR) Lateral Runout (TIR) Shaft End Play Shaft Radial Play	 0.002 in – 0.005 in 0.006 in 0.003 in	 0.002 in 0.002 in 0.002 in 0.005 in 0.002 in

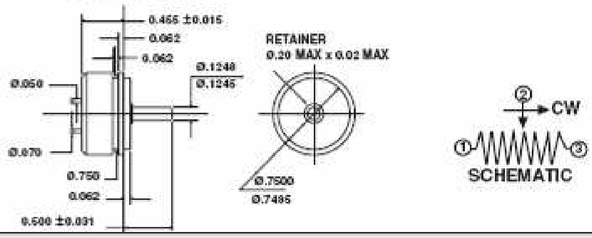
ORDERING INFORMATION			
157	1	1	XXX
MODEL	MOUNTING	NUMBER OF SECTIONS (SINGLE SECTION ONLY)	RESISTANCE EIA CODE
Example: 157 - 1 - 1 - XXX	1. Bushing 2. Servo		

DIMENSIONS in inches (mm)

BUSHING MOUNT



SERVO MOUNT



ALL DIMENSIONS ARE IN INCHES
TOLERANCES: UNLESS OTHERWISE NOTED
DECIMALS ± 0.005
ANGLES ± 2°

MATERIAL SPECIFICATIONS	
Housing/Bushing	Aluminum, anodized
Rear Lid	Ceramic
Shaft	Stainless Steel
Terminals	Solderable
Bushing Mount Hardware	Lockwasher, Internal Tooth Steel, Nickel Plated
Panel Nut	Brass, Nickel Plated

ENVIRONMENTAL SPECIFICATIONS		
Temperature	- 55°C + 125°C	
Rotational Life	BUSHING 10 million shaft Revolutions	SERVO 10 million shaft Revolutions
Moisture Resistant	Yes	
Vibration	15g 10 to 2000Hz	
Shock	50g	
Salt Spray	96 Hours	
Load Life	900 Hours	

STANDARD RESISTANCE VALUES

EIA CODE	RESISTANCE
102	1KΩ
202	2KΩ
502	5KΩ
103	10KΩ
203	20KΩ
503	50KΩ
104	100KΩ