

University of Southern Queensland  
Faculty of Engineering and Surveying

# Mobile Robot Guidance and Navigation

A dissertation submitted by

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In fulfilment of the requirements of

**Course ENG4111 and ENG4112 Research Project**

Towards the Degree of

**Bachelor of Engineering (Control and  
Instrumentation)**

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# Abstract

Autonomous robotic vehicle navigation relies on the vehicle being able to know where it is to an adequate degree of accuracy, and also to be able to sense the environment around it as required.

The purpose of this project, Mobile Robot Guidance and Navigation, is to design and construct hardware to interface sensors to the steering system of a mobile (wheel or track articulated) robotic vehicle.

Lab commissioning and field trials have shown the vehicle to be able to navigate over rough terrain while maintaining directional control.

Electronic compass resolution is 0.1 degrees, and maintains good stability when it is mounted clear of interfering devices when kept horizontal or error correction implemented.

Electronic compass based control for high-speed sub second positioning control is a practical way of maintaining stable control between longer interval GPS correction data.

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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.

Leslie Heath Airs

Student Number: Q9423076

A handwritten signature in black ink, appearing to read 'LHA', with a horizontal line extending to the right.

Signature

Wednesday, 26 October 2005

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Thanks to Dr. John Billingsley at USQ for an endless supply of ideas and advice as my project supervisor.

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Les Airs

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Monday, 24 October 2005

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# Chapter 1 - Introduction

## Background

Autonomous robotic vehicle navigation relies on the vehicle being able to know where it is to an adequate degree of accuracy, and also to be able to sense the environment around it as required.

The purpose of this project, Mobile Robot Guidance and Navigation, is to design and construct hardware to interface sensors to the steering system of a mobile (wheel or track articulated) robotic vehicle. This is presently the subject of an on-going research project involving the guidance and navigation of a model 'load-haul dump truck' at USQ based on 'peer differential' GPS. A brief assessment by myself, and input from Anders Loof (research student) of the performance of the present controls on this model truck suggest some shortcomings, namely;

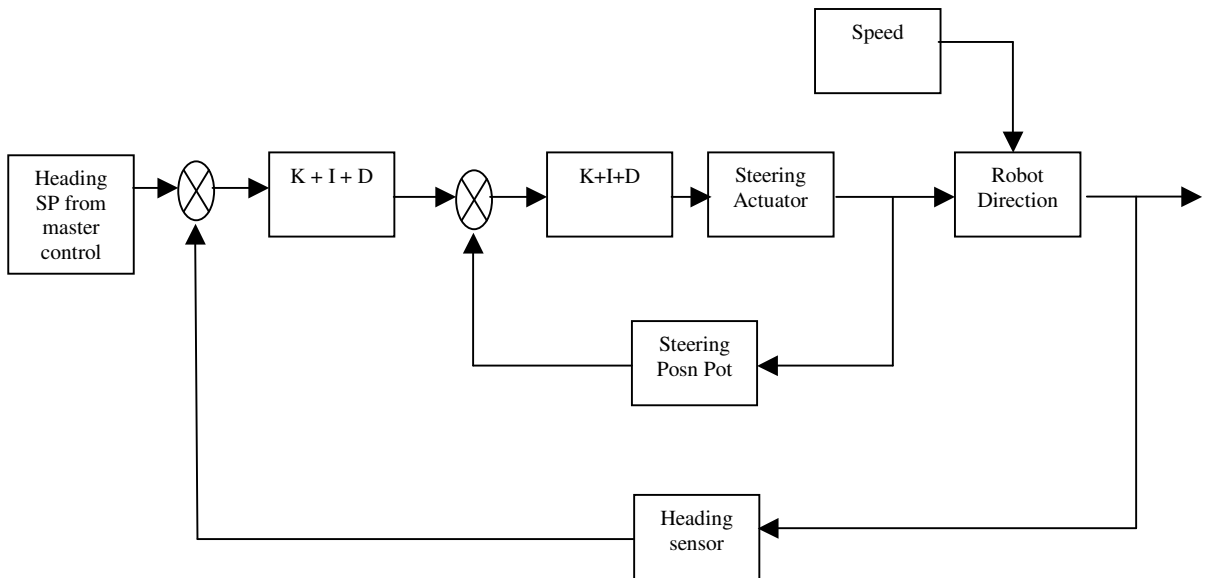
1. GPS position updates are one second 'old' by the time they are delivered to the navigation algorithm.
2. Odometry in rough terrain or loose soil will always have errors substantial enough to produce an overshooting response or a path representing a zigzag when being updated at one second intervals via GPS.

As this project is being developed mostly off-campus, the first problem will not be addressed due to the need for USQ's hardware to be off site for a considerable period. However, the second point above could be addressed by implementation of a high-speed directional control loop within the overall GPS control. This could enable high speed directional corrections within the GPS update period, keeping the vehicle on the heading setpoint despite odometry 'slip' and step changes due to rough terrain.

A heading sensor is required that can return the present heading of the robot at a high rate (much faster than the one update per second received from the GPS heading control system). It must also have a resolution suitable to keep the

vehicle on track within tolerance. It would then receive periodic heading updates from a GPS ‘master’ control, to maintain absolute position control.

Such a control system would look like:



*Figure 1 –Control loop for heading control*

Suitable heading sensors may be electronic or solid-state compass, gyroscopes, machine vision ‘vanishing point’ recognition, radar, sonar, the integral of an accelerometer, etc.

The research will focus on electronic compass for this application with some of the other sensors considered. The electronic compass promises to provide a reliable heading control with adequate resolution have a realistic development time for this project and be constructed and tested at a reasonable price.

## Project Objectives

The overall objective of this project is to *implement an effective electronic compass guidance system in hardware form, and demonstrate its functionality. Specifically, this should provide a robust high speed control loop that will provide good directional control within the sub-second timeframe, operable in a rural environment.*

Further work may then be done to place a ‘correction layer’ above this control based on peer-differential GPS, and then place a ‘control layer’ over this to provide navigation for the system.

The overall objective will be reached if the hardware is able to control a vehicle over relatively rough terrain while maintaining its bearing (heading), and also provide good recovery from transient disturbances in the sub-second timeframe. Drift off-course within the electronic compass specifications outside the sub-second timeframe will be acceptable, as this system is designed to have an ‘absolute’ correction applied to it at regular intervals, such as the (USQ, Dr John Billingsley) peer differential GPS system.

## Project Goals

The following goals will enable the Objective to be reached:

1. Define performance criteria to be able to conclude the 'objective' has been met.
2. Research previous implementations of electronic compass control and the problems and advantages of this form of control.
3. Assess the options for directional control and produce outline design of the system to be implemented.
4. Carry out experimental evaluation of the chosen system and assess it against requirements of (1)
5. Implement the directional control system in hardware form and again assess its performance via field trials.

Performance criteria will be based on realistic outcomes from the research. These criteria will then develop into a test plan to test against the criteria. This will be defined in the 'Implementation' chapter of this document.

As time permits, the following may be also investigated:

1. Research suitable radio telemetry systems with the aim of making the peer-differential GPS system at USQ 'wireless'.
2. Consider the placement of the peer differential GPS correction on top of the directional control to provide corrections to the system.

## Implications and Effects

Many people in many fields of study have been and are currently researching various autonomous navigation systems and tracking/location systems for mobile wheel or track type robots / vehicles. This is due to the benefits of such systems to aid human activities and needs. Uses are many and varied, some present uses are:

1. The military using unmanned vehicles to preserve human life, and also to improve the effectiveness of various war machines, such as the unmanned surveillance aircraft, which may stay in the air until refuelling is required.
2. Agriculture for the improvement of planting efficiencies and on large properties for border and watering trough surveillance.
3. Scientific research where the areas to be studied are remote (eg Mars, see the picture of the Mars rover below) or very dangerous (eg active volcano craters).
4. Emergency services where tasks are dangerous such as bomb disposal or nuclear reactor inspections, or for tracking locations of vehicles in areas where GPS coverage is poor.

The last two examples above still tend to rely very much on human 'remote control' rather than autonomous intelligent navigation.



*Figure 2 – The JPL / NASA Mars rover Spirit, artist's impression (source: [http://www.nasa.gov/vision/universe/solarsystem/30dec\\_gusevcrater.html](http://www.nasa.gov/vision/universe/solarsystem/30dec_gusevcrater.html))*

Some future uses of such guidance and navigation technology may be:

1. In passenger vehicles to allow an 'autopilot' mode, reducing accidents due to driver fatigue.
2. Automated mail/parcel/package delivery.
3. Factory parts delivery to work centres.
4. Geriatric care, enabling older citizens to travel despite reduced mobility, prolonging their self sufficiency.

Imagine ordering your shopping online, and then within an hour your order arrives at your door, delivered by an unmanned vehicle. Imagine a city where all deliveries are carried by small efficient unmanned vehicles, reducing pollution and improving efficiency. These are some benefits this technology may bring.

This technology may be seen by some to be 'giving up control of the machines' or in some ways reckless. But then autopilot systems in aircraft have been around since 1945 ( [http://www.honeywell.com/sites/aero/Our\\_History.htm](http://www.honeywell.com/sites/aero/Our_History.htm)), and it is readily accepted that a Boeing 747-400 with 400 passengers on board will be on autopilot for a large proportion of any international flight.

Cruise control in passenger vehicles is now largely a standard feature, and is readily accepted despite some of the control being handed over to the machine. This line of controllability is being pushed further every day; take the stability controls being built into passenger cars. These systems monitor steering position and where the vehicle is actually headed (using accelerometers) to take over braking and engine control to avoid a vehicle skidding out of control (Robert Bosch GmbH – Systems and Products for Automobile Manufacturer – Electronic Stability Program (ESP), viewed 3 June 2005 <[http://rbk.bosch.de/en/start/s3\\_esp.html](http://rbk.bosch.de/en/start/s3_esp.html)>) . We are slowly approaching autonomous operation of various subsystems of machine control, and we accept this readily, but the biggest hurdle for this technology is the barrier of taking the human driver out of the drivers seat, and allowing total control for operation of the vehicle to be via the machine.



This raises some ethical questions:

1. How far should a designer go to implement systems to ensure the vehicle does not harm people or place people at risk? To produce a 'risk-free' system, safety systems with redundant sub-systems, intelligent sensors, and other fail safe systems are required. This could be a very costly process. Through risk assessments would provide the solution to this question.
2. If a manned vehicle is involved in an accident, generally a human driver will take the 'blame', with little or no controversy. If a similar injury to a human is caused by an unmanned vehicle, who is to 'blame'? The owner of the vehicle? The manufacturer? The Engineers? The OEM equipment supplier? Perhaps all parties would share some blame. It would be certain though, that unlike a human 'mistake', doubt would fall upon all other unmanned vehicles in operation as well. This situation must be avoided at all costs if the technology is to move forward.

Present implementations of this technology, in the air, on the battlefield, on rural properties or in remote dangerous environments, pose little threat to human kind. Where there is some risk, proper risk assessment and system design to minimise the risk is required.

## Chapter 2 – Guidance Systems

## Literature Review and Technical Survey

The Literature review will encompass the following points:

1. Is the earth's magnetic field suitable for mobile robot guidance and navigation?
2. What errors and performance can be expected from electronic compasses?
3. Research of previous implementations of electronic compass control and the problems and advantages of this form of control (including error correction).
4. Research the control theory required to achieve stable control using multiple inputs into a single output system. (Kalman filter)

### The Earth's Magnetic Field

Electronic compasses rely on the earth's magnetic field for their operation, so it is important to assess the suitability of both the electronic compass and the earth's magnetic field in relation to the application of mobile robot guidance and navigation.

The earth's magnetic field has been a navigation tool since the 13<sup>th</sup> century when the 'Mariner's Compass' was used at times when the North Star was obscured. Early users of compasses were untrusting of them, as there was always an error between true and magnetic north. As time passed, this attribute of the earth's magnetic field was studied, compass corrections were documented and then the perception of the compass changed to that of an important navigation tool (The History of Navigation 2000, viewed 22/10/2005 <<http://www.boatsafe.com/kids/navigation.htm>>).

When lava erupts from volcanos and hardens, it leaves evidence of the earth's magnetic polarity. Geologic studies of this have shown that the earth's magnetic field reverses direction on average every 200,000 years. However, the last time the earth's magnetic field reversed was 780,000 years ago. Studies have also shown that the earth's magnetic field has weakened by 10 percent since magnetic field strength records first begun in 1845. (Roach, The Earth's Magnetic Field Is Fading 2004, viewed 01/04/2005 <[http://news.nationalgeographic.com/news/2004/09/0909\\_040909\\_earthmagfield.html](http://news.nationalgeographic.com/news/2004/09/0909_040909_earthmagfield.html)>)

Modern studies of the earth's magnetic field show that it is a dynamic system, known as Earth's 'geodynamo'. The slowly and constantly changing convection currents in the earth's liquid core are thought to create the earth's magnetic field.

The U.S. National Geophysical Data Centre maintains a 3-dimensional model of the earth's magnetic field. This model can give accurate information about the present magnetic field parameters anywhere on or above earth, and can also give model-based predictions on the field parameters into the future. This model can be found at [www.ndgc.noaa.gov](http://www.ndgc.noaa.gov). When the latitude, longitude, and elevation of my home address were entered into the U.S. National Geophysical Data Centre model, the following information about the magnetic field at my location was obtained:

**Results for my back yard, date: 2005.7123**

**Declination** = 10.556° changing by -0.003 °/year

**Inclination** = -56.685° changing by 0.005 °/year

**X component** = 28,612.6 changing by -11.47 nT/year

**Y component** = 5,331.89 changing by -3.56 nT/year

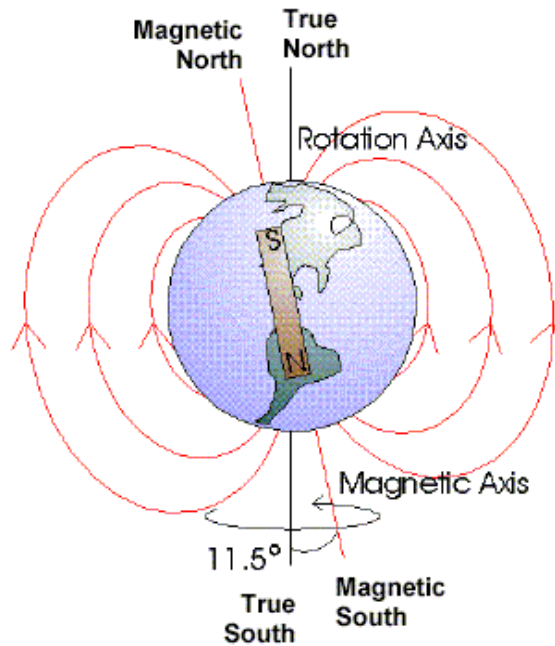
**Z component** = -44,282.4 changing by 26.57 nT/year

**Horizontal Intensity** = 29,105.15 changing by -11.93 nT/year

**Total Intensity** = 52,990.95 changing by -28.75 nT/year

The interesting points to take out of this is the Inclination value, which is the angle the 'flux lines' of the earth's magnetic field make with the tangent plane to the earth's surface; and the Declination, which is the angle between magnetic north and 'true' geological north. Note that the declination is changing at a rate of -0.003 °/year, therefore is suitably stable for sub-second control.

The next section on ‘electronic compasses’ explains how the declination of the earth’s magnetic flux lines affects the accuracy of electronic compasses when tilted. The figure below shows graphically that the flux lines only run tangent to the earth’s surface at (approximately) the equator. At any other point, the tilt error of the compass will need to be taken into account.



*Figure 3 – Illustration of the earth's magnetic field*

From the above information (with respect to the goal to implement a fast, sub second control loop), the earth’s magnetic field is stable and reliable enough to use as a guidance parameter.

## Electronic Compasses

Electronic Compasses simply detect the earth's magnetic field in either two-axes or three-axes and compute from the relative magnitudes the present heading.

The sensors used in commercial electronic compasses are:

- Fluxgate sensors – These have a drive coil and sense coil. The drive coil current used to saturate the core in one direction is compared to that in another direction. The difference is due to an external magnetic field (<http://beale.best.vwh.net/measure/fluxgate/>)

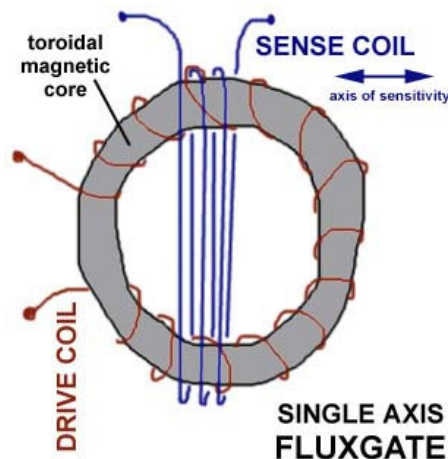


Figure 4 – Single Axis Fluxgate (source: <http://beale.best.vwh.net/measure/fluxgate/>)

- Magneto-resistive. These consist of a magnet with a wire wound around it. A constant current is passed through this wire. As the magnetic field changes (either because of proximity to other metallic objects, or the change in the earth's magnetic field), the impedance of the coil of wire changes. ([http://everything2.com/index.pl?node\\_id=569396](http://everything2.com/index.pl?node_id=569396))
- Magneto-inductive. This is a system patented by PNI corp. These change inductance as the magnetic field changes.
- Mechanical, with optical transducers. This is simply a traditional suspended magnetic needle, with some kind of optical (or other) sensing of the needle position.

Electronic compasses can output heading and magnetic field information in various formats. This output can be as simple as the analog representation of field strength of the sensor on each axis as an output voltage, or as advanced as a digital calibrated high-resolution output on a serial bus such as the inter integrated circuit bus or I<sup>2</sup>C bus. Most electronic compasses have several outputs or several output modes to give the end-user a choice as to the format they receive the data in.

Choosing the format of the electronic compass output is important if error correction is to be used. For example, a digital value corresponding to heading may be convenient, but contains no information about field strength that may be used for error detection and correction.

Chapter 3 contains specific information about various electronic compass modules available, and explains how the trial model was decided upon.

## Implementations of electronic compass control

### The Mini Rover 7



*Figure 5 – The ‘Mini Rover 7’ Miller, J 2004, ‘Mini Rover 7’, Circuit Cellar Magazine, Issue 165 April 2004, pp. 14-22*

In the article by Joseph Miller describing his model based on NASA’s Mars rover, (Miller, J 2004, ‘Mini Rover 7’, *Circuit Cellar Magazine*, Issue 165 April 2004, pp. 14-22) the implementation of dead reckoning navigation utilising an electronic compass is discussed. Dead Reckoning (DR) is described as a mathematical method of tracking your present location by measuring speed (or distance) and the direction travelled at regular intervals, and computing a present location from this information. For the Mini Rover 7, Miller uses the PNI V2Xe electronic compass utilising magneto-inductive sensors to determine his robot’s heading (see notes on the V2Xe compass in the ‘Selection of Compass Module’ section of this document).

Miller conducts several experiments on the compass module including hard iron and soft iron offset measurement. His results are tabulated in graphical form below:



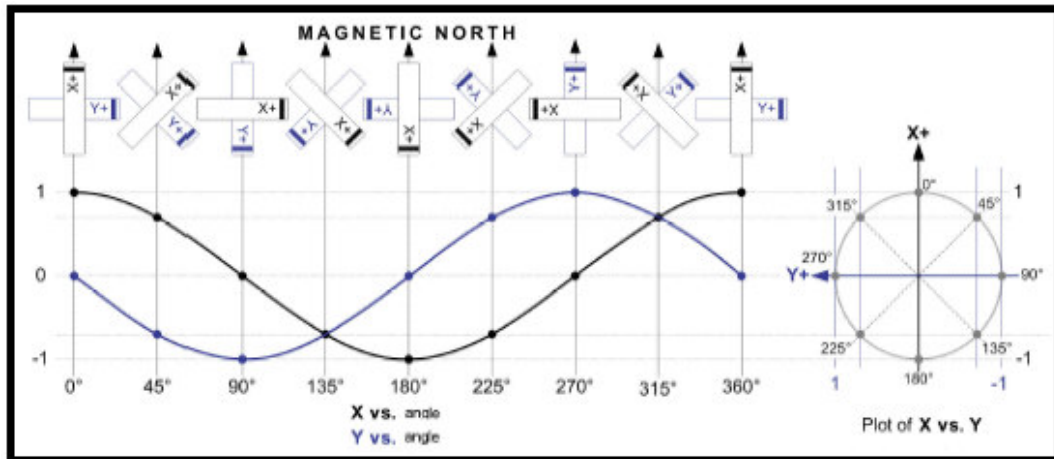


Figure 6 - Magnetometer sensor output vs angle; linear and x-y plots. 'Figure 2' of Miller, J 2004, 'Mini Rover 7', Circuit Cellar Magazine, Issue 165 April 2004, pp. 15

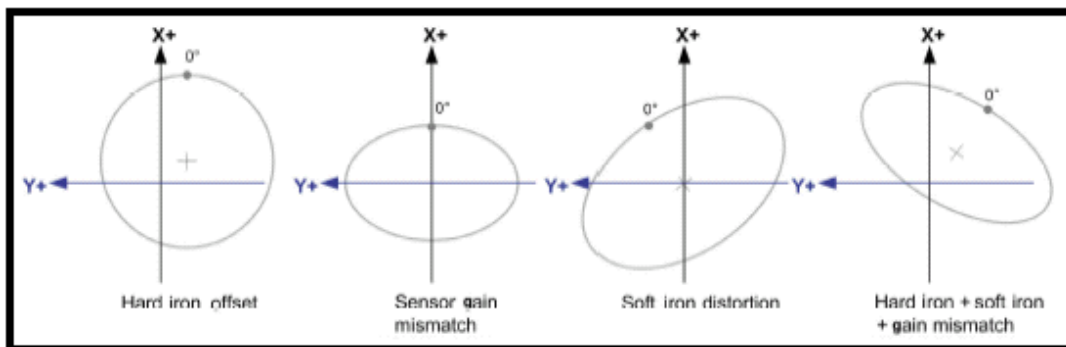


Figure 7 - Magnetic distortion effects. From 'Figure 3' of Miller, J 2004, 'Mini Rover 7', Circuit Cellar Magazine, Issue 165 April 2004, pp. 18

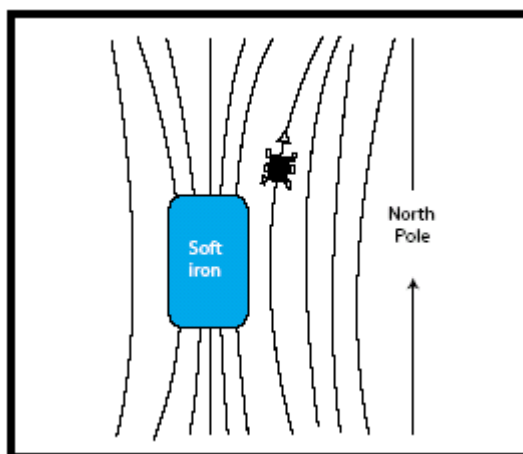
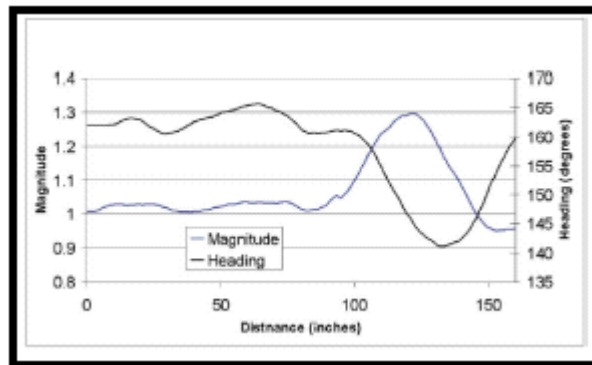


Figure 8 - An illustration of the effects of 'soft iron' distortion on the earth's magnetic field; From 'Figure 4' of Miller, J 2004, 'Mini Rover 7', Circuit Cellar Magazine, Issue 165 April 2004, pp. 18



*Figure 9 - Practical experimental results from a compass guided robot travelling in a straight line. From 'Figure 7' of Miller, J 2004, 'Mini Rover 7', Circuit Cellar Magazine, Issue 165 April 2004, pp. 22*

Figure 7 of Miller above, shows the feedback from an electronic compass on board a robot travelling in a straight line down the corridor of the authors home. At around the 100 inches mark, the robot passes the kitchen and the rear of a refrigerator. The heading veers off course at this point, while the magnitude of the magnetic field increases dramatically. Thus the departure of the magnitude of the magnetic field from a 'normal' value may be a good indicator of the quality of the heading information received.

Miller then repeats his experiments in an outdoor environment and does not find any of the magnetic disturbances as above. This is promising for the rural application of this research project. Miller does not provide any data on outdoor experiments, so this is one area where I will have to do my own investigations.

#### Compact Outdoor Multipurpose Pose Assessment System (COMPASS)

This is a system built by Omnitech Robotics, Colorado, designed to be fitted to military vehicles to enable vehicle position and orientation estimates. Differential carrier-phase GPS, 3-axis accelerometer, 3-axis rate gyro, Flux-gate compass, 2-axis inclinometer and wheel encoders are processed through a Kalman filter algorithm to produce the position and orientation estimates. Source: [http://www.omnitech.com/pdf/compass\\_ds.pdf](http://www.omnitech.com/pdf/compass_ds.pdf)



*Figure 10 - The COMPASS hardware. From compass\_ds.pdf, Omnitech Robotics 2000, pp2*

#### Vehicle Navigation Unit (VNU)

This unit produced by Point Research Corporation, using technology also developed for the US army, is similar in function to the COMPASS above. It allows a wheeled vehicle's position to be tracked where GPS signals may be non-existent (eg in underground car parks). This unit combines absolute GPS signals with dead reckoning through a Kalman filter to produce the vehicles present location. Dead reckoning is achieved through an odometer, 3-axis accelerometer, electronic compass and azimuth gyro, providing location data when there is a loss of GPS signal or interference. Source: [http://www.pointresearch.com/vnu\\_sheet.htm](http://www.pointresearch.com/vnu_sheet.htm) An interesting demonstration of point research's dead-reckoning module vs. GPS can be seen at [http://www.pointresearch.com/map\\_demo.htm](http://www.pointresearch.com/map_demo.htm)



*Figure 11 - The VNU Hardware.* From Point Research, 2004, brochure, viewed 30/05/05, <[http://www.pointresearch.com/vnu\\_sheet.htm](http://www.pointresearch.com/vnu_sheet.htm)>

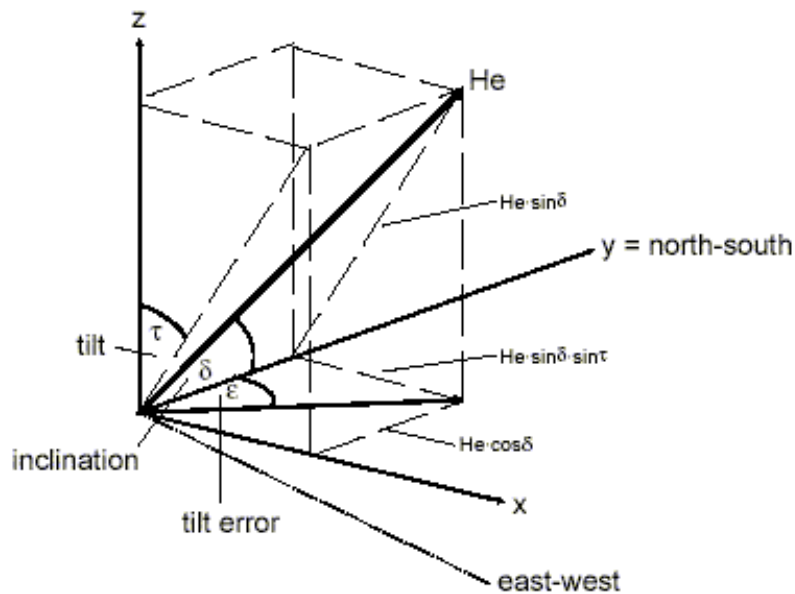


*Figure 12 - The VNU CPU.* From Point Research, 2004, brochure, viewed 30/05/05, <[http://www.pointresearch.com/vnu\\_sheet.htm](http://www.pointresearch.com/vnu_sheet.htm)>

## Errors and Performance of Electronic Compasses

Electronic compasses can experience errors other than the ‘hard iron’ and ‘soft iron’ interference detailed by Miller above. Two-axis compasses by their nature will produce an error if the compass is not pointing directly to magnetic north and the compass is tilted.

The following diagram explains the reason behind this.



*Figure 13 – Vector representation of earth’s magnetic field. From Phillips application note AN00022 “Electronic Compass Design using KMZ51 and KMZ52”*

In the above diagram, the earth’s magnetic field flux line is expressed as ‘He’. The angle ‘He’ makes with the tangent plane to the earth’s surface is the inclination. When the compass is horizontal, the tilt is zero, and there is no tilt error. If the tilt is increased, as shown above, ‘He’ is detected in a false plane, and the projection of ‘He’ is no longer correct, resulting in the ‘tilt error’ shown.

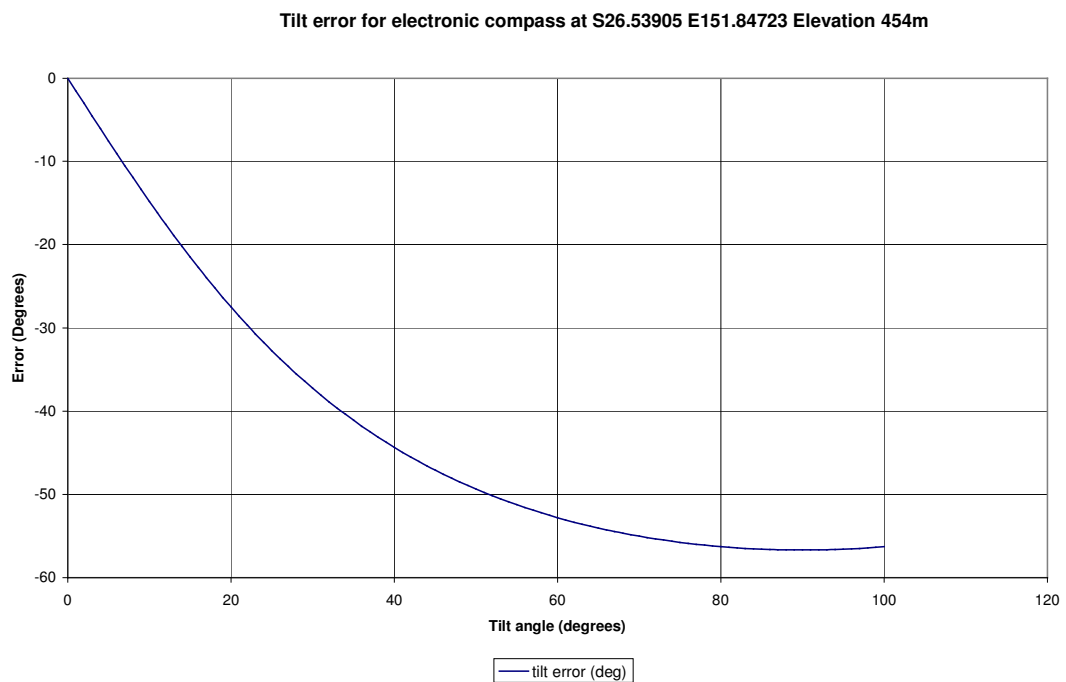
This tilt error can be expressed as (Stork, Thomas 2000, *Electronic Compass Design using KMZ51 and KMZ52*, Phillips Semiconductor, Germany):

$$\mathcal{E}_{\max} = \arctan \frac{He \cdot \sin \delta \cdot \sin \tau_{\text{east-west}}}{He \cdot \cos \delta}$$

$$\mathcal{E}_{\max} = \arctan(\tan \delta \cdot \sin \tau_{\text{east-west}})$$

The above equation for error was plotted against magnetic field data from the U.S. National Geophysical Data Centre for S 26.53905, E151.84723, Elevation 454m (my home address). The only data required to plot the expected error due to tilt is the angle of inclination as per the equation above.

A plot of the error vs. tilt follows:



*Figure 14 – Tilt error for electronic compass at S26.54 E151.84 Elevation 454m*

The above chart indicates that for small amounts of tilt (less than 20 degrees) the error is roughly linear at 1.5 degrees error for every degree of tilt. Thus it is concluded that tilt of the 2-axis compass can produce very major heading errors.

If the amount of tilt is known accurately, the formula:

$$\mathcal{E}_{\max} = \arctan(\tan \delta \cdot \sin \tau_{east-west})$$

Can be used to 'compensate' the tilt error, thus providing an effective method of tilt compensation. This could be as simple as a damped pendulum with position feedback to indicate the angle of departure from the horizontal.

The 3-axis compasses on the market claim to implement tilt compensation to alleviate the tilt problem. They sell at a price premium of ten times or more than that of the 2-axis module.

## Error Correction Techniques for Electronic digital compass

### Magnitude of magnetic field

This technique as noted in Miller, is implemented by monitoring the magnetic field strength from the electronic compass. The earth's magnetic field strength will be constant relative to the geographical location, and will not vary by a large degree as the compass moves. Magnetic interference, either by 'hard iron' sources (such as electric motors, radio transmitters etc), or soft iron sources (steel sheds, large ferrous objects), will show up by an increase or decrease in magnetic field strength. This deviation from normal field strength can then be interpreted as cause of a possible error and the heading data from the compass can then be regarded as 'suspect'.

### The Kalman Filter

The 'Kalman Filter' has appeared widely in the literature studied above, and is worth mentioning due to its extensive use in combining various sensory information into a useable position estimation, compensating for the 'noise' appearing on the sensors. Simon (2001) defines a Kalman filter in mathematical terms as an estimator of a linear system, and that it minimises the variance of the estimation error. What this means in practice is that several 'noisy' inputs can be processed by the Kalman filter to give useable and smooth position estimation output.



## Evaluation of Alternative Solution

Mechanical Gyroscopes are an alternative heading sensor. They are simply based around a spinning wheel mounted in a gimbal mount. To achieve high accuracy they require precision machining and high-quality components. This can make their purchase price well in excess of \$10,000 US. Price alone makes this type of gyro unsuitable for this project.

Other less expensive Gyros are available, such as fibre-optic, and other low-cost mechanical gyroscopes, priced as low as \$150US. These low cost gyroscopes are also low precision, with drifts in the order of tens of degrees per minute, making them too imprecise for this project.

Optical gyros in IC packaging are also under development, but won't be considered for this project.



*Figure 15 – mini gyroscope as used in hobby model aeroplanes*

*<http://www.minihobby.com/electronics/pgyro.jpg>*

## Research Summary

The Literature Reviews undertaken displayed a common theme; electronic compasses are widely used as part of heading control systems that also incorporate GPS and odometry to provide position information. This information is often combined by the use of the Kalman Filter to produce the best possible estimation given the types of errors associated with electronic compasses, GPS and dead reckoning.

The strengths of using the electronic compass in the dead reckoning loop are:

- Accumulated heading drift is minimised, compared with using steering position sensors.
- Heading errors created by rough terrain can be corrected immediately, without waiting for the next GPS position update.
- Where steering sensors cannot detect heading error due to rough terrain, the electronic compass is able to detect the heading change.

Weaknesses of using electronic compass in the dead reckoning loop are:

- Compass tilt can significantly affect the compass reported heading. A two-axis compass must be kept horizontal at all times for correct heading to be obtained. This can be done by gimbal mounting the compass. 3-axis compasses are able to automatically compensate for the tilt of the compass module.
- Compass heading can be affected by hard and soft iron distortions. Static hard and soft iron distortions produced by the robot's body and systems can be calibrated out easily. Hard and soft iron distortions caused by the environment (eg electric motors, large metal buildings etc) cannot be compensated for. As this project is designed to be operated in a rural environment, this is not such a concern due to the lack of interfering objects. If the compass was to be used in a residential or commercial / industrial setting, error correction functions of the Kalman Filter and also

other error correction methods such as magnetic field strength tracking would be required.

From the cases outlined above it is clear that digital, electronic compasses can and do play an important role in mobile robot navigation systems, especially where dead reckoning is required to allow for GPS outages. It is also noted that extensive use of the Kalman filter is made in these systems to integrate the sensor data into one useable output.

## Chapter 3 - Implementation

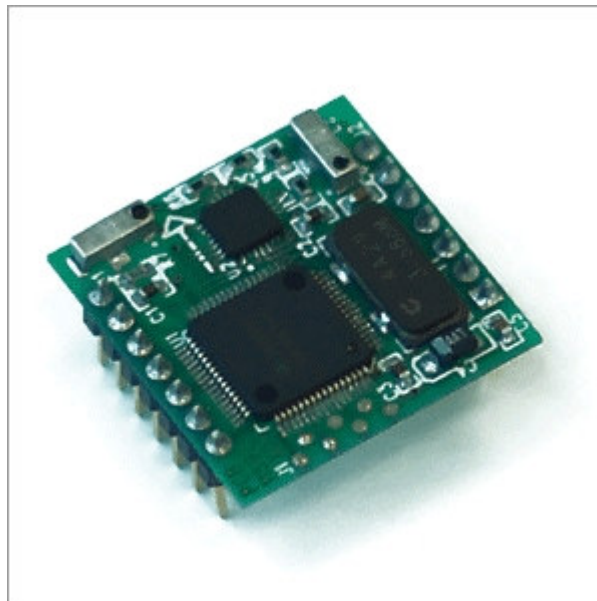
## Selection of Compass Module to evaluate

There are several electronic compass variants that are suitable:

V2Xe by PNI (Vector 2X(e))

1. 2-axis unit
2. resolution of 0.01 degrees
3. supply current of < 2mA @ 3VDC
4. Magneto-Inductive (MI) sensors (By PNI)
5. Heading Accuracy of 2 degrees (calibration required)
6. Motorola SPI protocol output for serial connection to host processor
7. Price \$75 US (approx \$100 AU)

Source: <https://www.pnicorp.com/productDetail?nodeId=c39b>



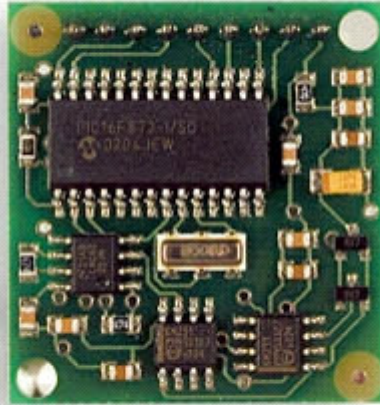
*Figure 16 - The V2Xe compass module by PNI Corp.*

Devantech CMPS03 - Philips KMZ51 magnetic field sensor,

1. 2-axis unit
2. resolution of 0.1 degrees
3. supply current of 20mA @5VDC
4. Philips KMZ51 magnetic field sensor

5. Heading Accuracy of 3 degrees (calibration required)
6. I2C and PWM outputs
7. Price 22.12 GBP or \$85 AU

Source: [http://www.robot-electronics.co.uk/shop/Compass\\_CMPS032004.htm](http://www.robot-electronics.co.uk/shop/Compass_CMPS032004.htm)

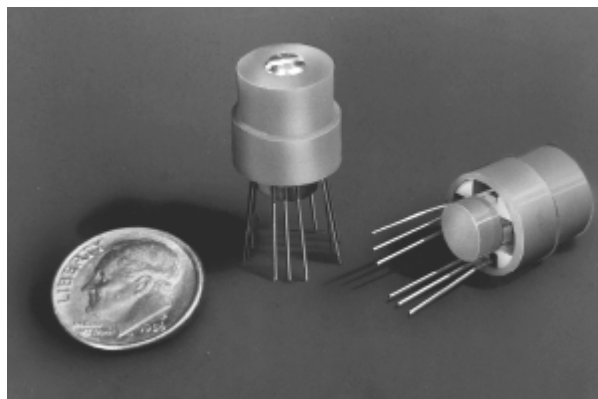


*Figure 17 - The Devantech CMPS03 module*

#### Dinsmore 1625

1. 2-axis unit
2. analog output on both axis (requires decoding for heading)
3. supply current of 19mA @ 5VDC
4. Hall Effect sensor to detect rotation of compass needle (mechanical field sensor)
5. Price approx \$35 US (\$46 AU)

Source: <http://www.dinsmoresensors.com/1655spec.htm>



*Figure 18 - The Dinsmore 1625 sensor.*

## TCM2 by PNI

1. A 3-axis tilt compensated unit ('electronic gambling')
2. Resolution 0.1 degree
3. Output is RS232C or NMEA0183
4. Input 5VDC @ 20mA
5. Magneto-Inductive (MI) sensors (By PNI)
6. Accuracy of 0.8 degree
7. Price: \$719.00 US (approx \$954 AU)

Source: <https://www.pnicorp.com/productDetail?nodeId=cTCM2.5>



Figure 19 - The TCM 2.5 Compass Module by PNI Corp.

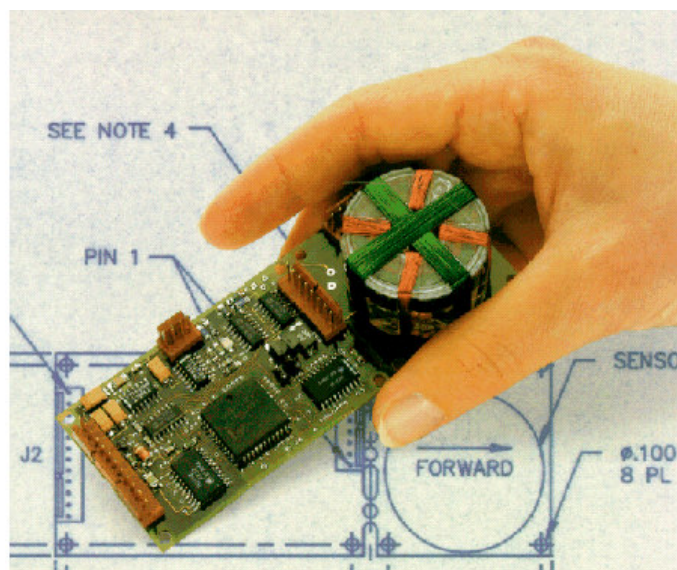


Figure 20 - Fluxgate magnetometer, manufactured by KVH.

Of the above listed contenders to be used in the trial, the Devantech CMPS03 utilising the Philips KMZ51 magnetic field sensor has been chosen because:

- Purchase price is relatively low (\$85 AU)
- It has I2C outputs which interface directly to the PICAXE microcontroller which is to be used in the project
- Durable surface mounted component construction
- Output resolution of 0.1 degree
- Internal calibration and compensation routines
- Known supplier, and quick delivery



## Design Constraints and Feasibility

As stated in the opening comments, the overall objective of this project is to *implement an effective electronic compass guidance system in hardware form, and demonstrate its functionality. Specifically, this should provide a robust high speed control loop that will provide good directional control within the sub-second timeframe, operable in a rural environment.*

This has to be achieved to a budget set by myself, and be able to be constructed using standard workshop tools and facilities that are available to me at my workplace (the Tarong Power Station).

Given time constraints, a suitable pre-constructed test vehicle platform would be ideal. This already exists in the form of 'robocow', from a previous robotic navigation project at USQ. To as fully as possible simulate a rural vehicle with 'car-like' steering such as a tractor, a different design is required, and has been found in the form of a ready to assemble 'garden-cart', only requiring a rear drive and steering actuator and encoders / odometry to be fitted.

# Proposed Design

## Requirements

A summary of the information gained has been assembled to create requirements for the design of a test robot.

- Compass control must provide high speed corrections to steering actuator
- Simulations to be carried out to test design of hardware and software
- Performance of the system must be measurable (ie. the 'states' of the system must be logged for performance assessment)
- Test base (vehicle) must be robust to test in an outdoor 'rural' environment

## Sub-system Requirements

The following sub systems will need to be assembled before field tests of the robot are able to proceed:

- Steering angle closed loop control (including steering actuator and steering position feedback).
- Motor speed control (Pulse Width Modulated control is the preference)
- Compass unit
- Control unit to set speed, direction and provide close-loop control of the required steering angle to achieve the correct heading.
- Power distribution and control (including 12V battery, charging, protection, regulation and distribution circuits).

# Hardware and Sub-system Design

## Controller

- The PICAXE ‘flash’ memory based microcontroller has been chosen because its’ low cost and basic programming language should guarantee ease of use. The model microcontroller I am using is based upon a Microchip PIC16F873A microcontroller with the PICAXE ‘bootstrap’ program loaded. This enables the microcontroller to be programmed direct from a PC serial port. The assembler program for PC is available free from the PICAXE website, [www.picaxe.co.uk](http://www.picaxe.co.uk). The PICAXE also implements I2C communications with other devices easily. This feature will be exploited to make design and construction faster and easier than using ‘traditional’ IC and device interfacing methods.

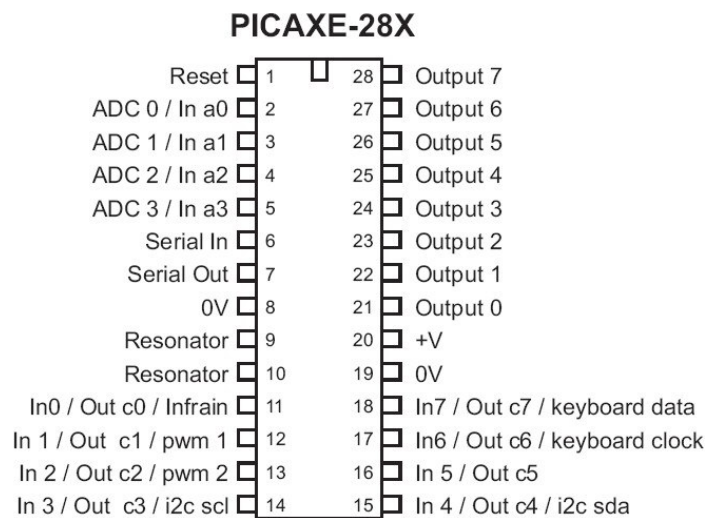
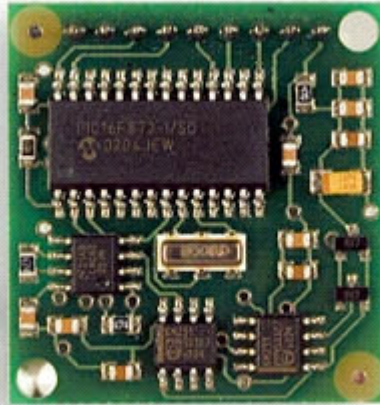


Figure 21 – PICAXE pinouts (source: [www.picaxe.co.uk](http://www.picaxe.co.uk))

### Electronic Compass

- Compass Board by Devantech CMPS03; see section on selection of compass module for details.



*Figure 22 – CMPS03 by Devantech*

### Odometry

- Not to be implemented for the ‘heading control’ trial. May be implemented at a later date using optical encoders (such as those from a computer ‘ball type’ mouse)

### Hardware platform

- ‘Garden Cart’ – chosen due to it’s ruggedness, pre built ‘car like’ steering, and size suitable for testing in outdoor rural environment



Figure 23 – The Garden Cart Packaging

#### Drive Motor

- 250W ‘Electric Bicycle’ motor – chosen because of ready mounted drive sprocket, fully enclosed motor / gearbox providing ruggedness, and sufficient output power.

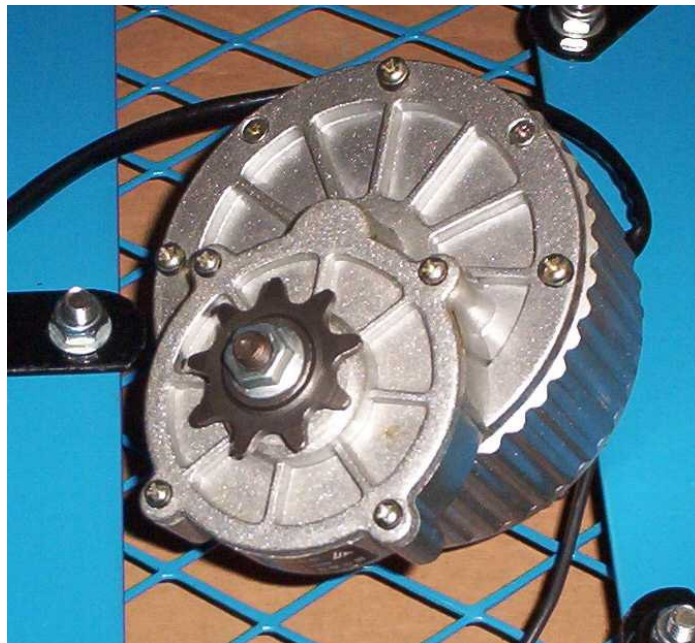


Figure 24 - The ‘electric bicycle’ motor to be used in the project

### Steering Servo

- Windscreen wiper motor – chosen due to fast slew rate, high torque output.



*Figure 25 - The ‘windscreen wiper’ steering actuator to be used in the project*

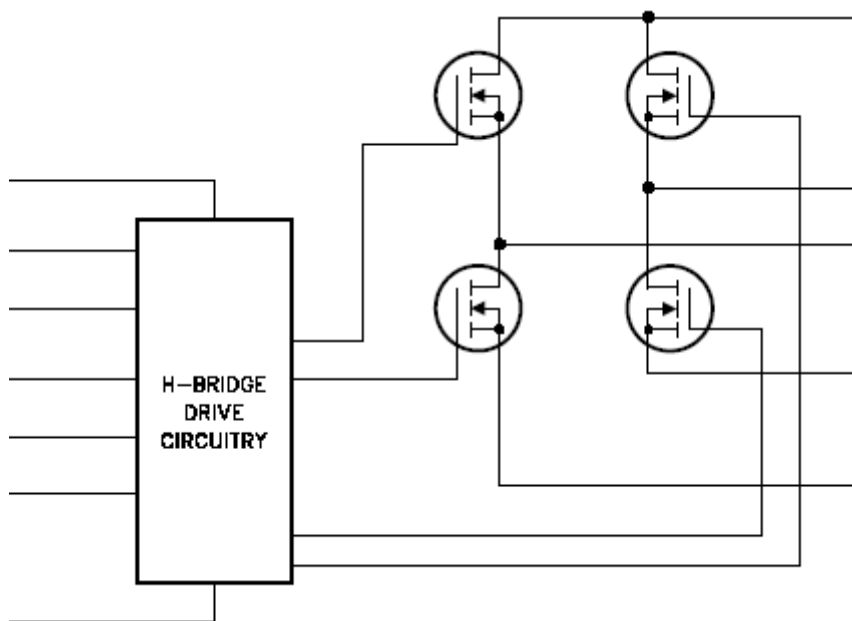
### Power Supply

- Sealed Lead Acid battery, 12Volts, 17 Amp-Hour – chosen because of high storage capacity, and low impedance providing good voltage regulation during motor / power electronics switching. Risks associated with the use of lead-acid batteries are covered in *Health, Safety and Environment* section.

## Power Electronics

A suitable H-bridge design was investigated. Power (high current) MOSFET's are required as the power handling part of the H-bridge to enable it to carry the full-load current of up to 15 amps DC at 12 volts, and to have the ability of pulse width modulation of the output for speed control of the drive motors.

The original design idea was to use the microcontroller output pins to select the forwards and the reverse mode of the H-Bridge, and then have this signal 'chopped' using external logic and the PICAXE microcontroller's Pulse output pins. The H-bridge would then only require some interfacing logic, providing the MOSFET drive signals and the interlocking function, ensuring that two MOSFET's on the same 'leg' of the H-Bridge do not energise at the same time, causing a short circuit across the 12V supply.



*Figure 26 - An example H-Bridge design*

*(<http://www.mskennedy.com/media/documents/4226rb.pdf>)*

Commercial H-bridge devices are also available. The MD22 by Devantech is a Dual (able to drive two motors independently) H-bridge drive (incorporating 8 x 27 amp MOSFETS) with an on-board microcontroller providing analog, PWM and I<sup>2</sup>C inputs. The unit as standard is rated at 5 amps continuous current. With



heatsinking, the continuous current draw can be increased to the MOSFET's maximum continuous rating of 27 amps.



*Figure 27 - The MD22 by Devantech*

After assessing the time and cost involved in manufacturing the H-Bridge circuit from discrete parts, it was decided that the \$160 purchase price of the MD22 was justified, because of its suitability for this project and the simplicity of connection to the PICAXE microcontroller via the I<sup>2</sup>C bus.

### Human Interface

The initial consideration of the human interface proposed the following:

- LCD display for useful information and setting during testing
- Keyboard / pot for setting entry
- Serial to PC for detailed setting / data retrieval

After further consideration, and determining the core requirements to achieve the objectives of the project, the LCD / Keyboard option was dropped, due to the time / expense in implementation and the ability to carry out the functions of these devices via a laptop PC using a serial interface to the PICAXE.



## Test plan and performance criteria

### Outdoor response of electronic compass test plan

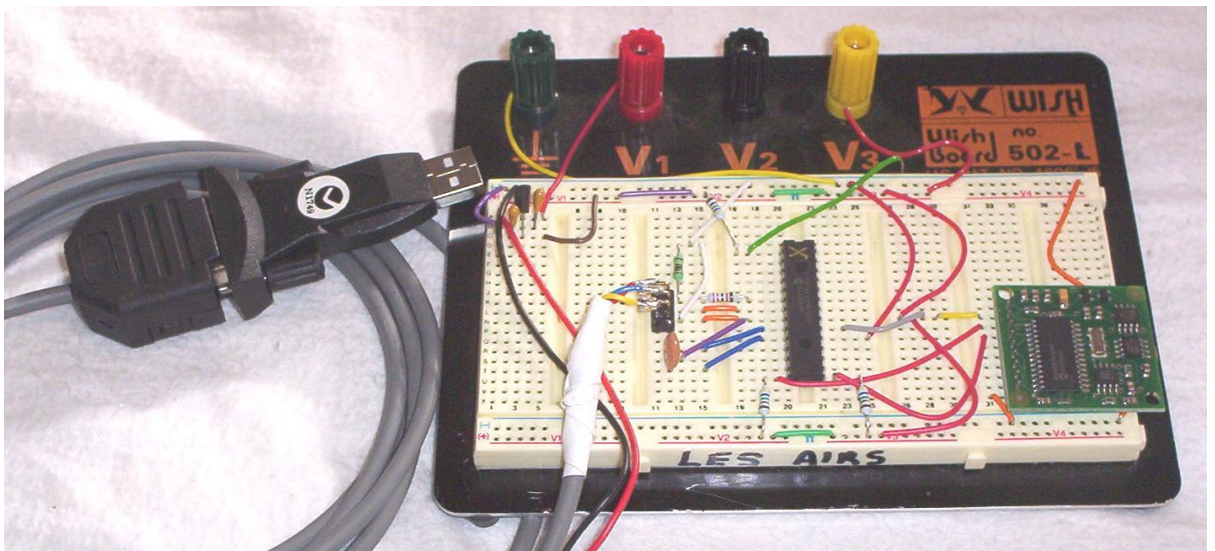
This is a series of experiments to determine the response of the compass module in an outdoor environment. Tests will include:

- Static drift test (accuracy and heading change over time)
- Step response test
- ‘Slew’ rate test

Test ‘pass’ criteria will be:

- Drift of less than 0.4 degrees per minute
- Noise of less than 0.2 degrees between any two consecutive heading samples
- Slew rate of at least 90 degrees per second

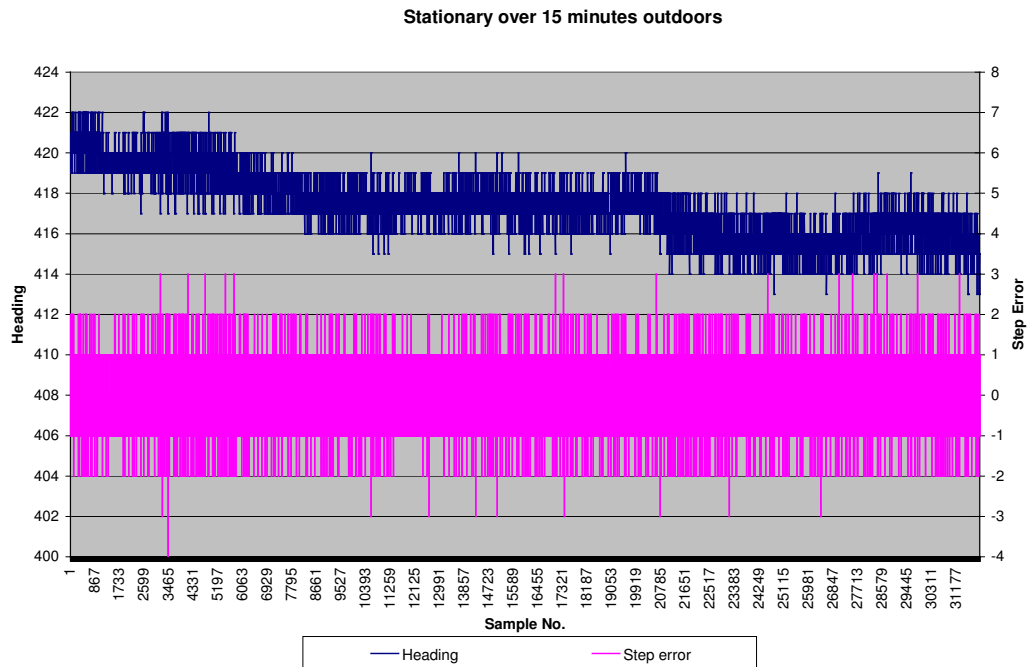
A test circuit was built based on the Devantech CMPS03. This test circuit is pictured below.



*Figure 28 - The robot control on breadboard. CMPS03 on right interfaces to a PC through a PICAXE controller*

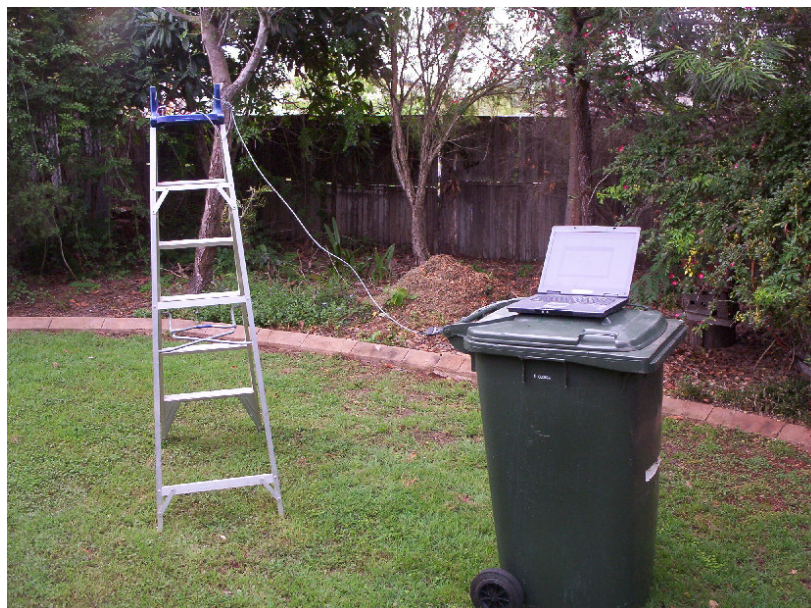
## Response of electronic compass – results

The compass was tested in an outdoor location, and in an indoor location to compare results.

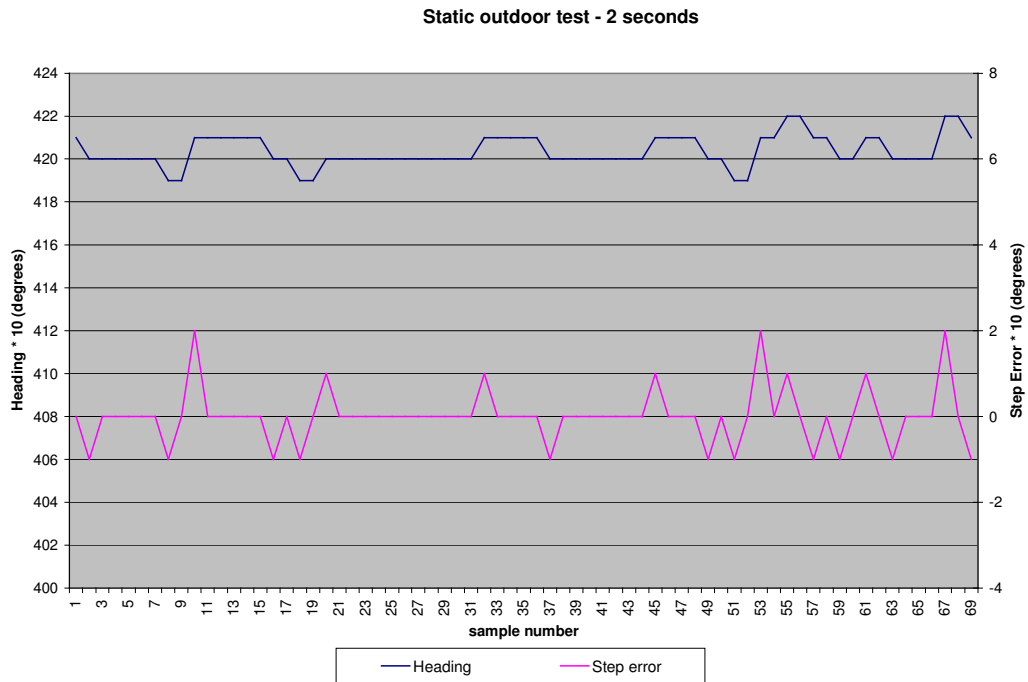


*Figure 29 – outdoor 15 minute test*

The outdoors test confirmed that some noise existed in the long term, and that the difference between consecutive readings ('step error' on the chart) was on average just larger than 0.1 degree, but regularly up to 0.2 of a degree.

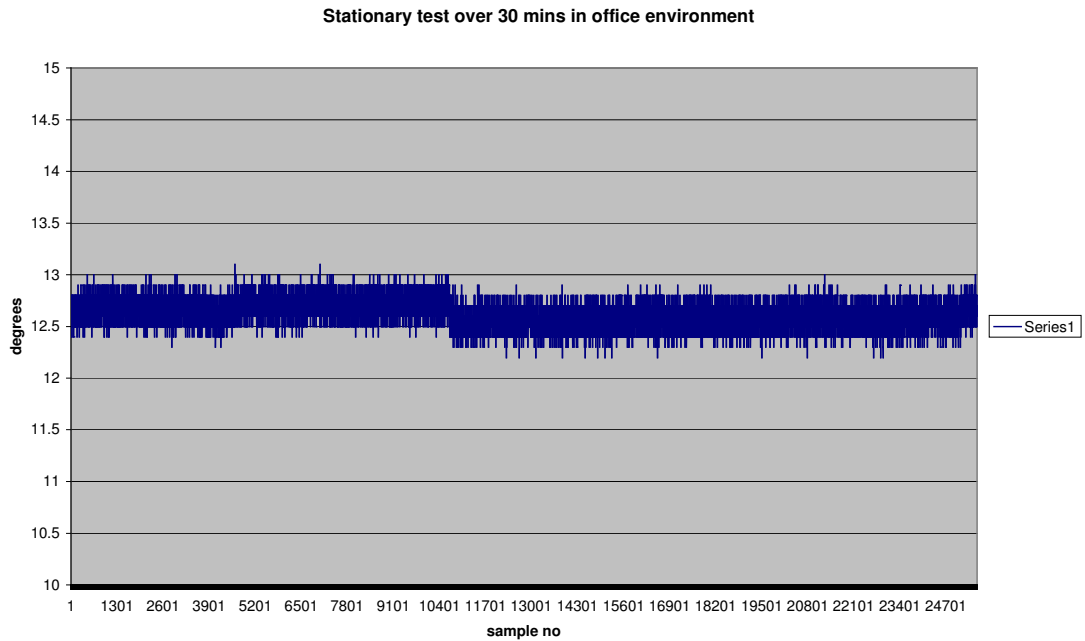


*Figure 30 – Outdoor static test set-up*



*Figure 31 – Outdoor 2 second test*

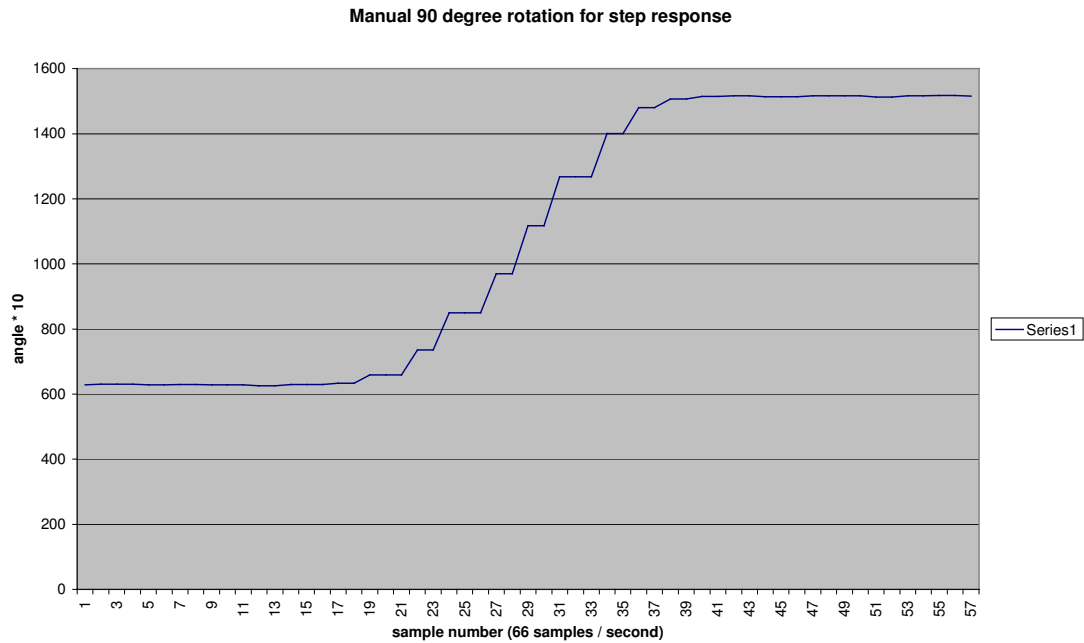
The same results over 2 seconds show a maximum error of 0.2 degrees and a maximum step between samples of 0.2 degrees. This indicates that some filtering or error correction may be required.



*Figure 32 – Indoor 30 minute test*

As can be seen, the office environment was quite noisy, with an average deviation of 0.4 degrees, twice the error of the outdoor environment, due to the proximity to PC switchmode power supplies, fluorescent lighting, and also being

within 50 metres of 275kV power distribution lines. The 'noise' exhibited in this office environment is typically 0.4 degrees (pk-pk).



The above step response test was carried out by manually rotating the compass approximately 90 degrees by hand, as fast as possible. The sample rate was 66 samples per second, thus the above 90 degree step was sensed by the compass in approximately 1/3 of a second. This may be the speed of the physical movement, but it does demonstrate that the slew rate must be better than 90 degrees per second as specified in the test criteria.

## Robot testing plan and performance criteria

The 'test plan' is:

- Assess each subsystem is functioning correctly via simulating an input signal and measuring the output.
- The closed loop steering / heading control will be tested without the drive motor operational to check the whole guidance system functionality.
- The robot will be given the task of maintaining a heading over a length of 20 to 50 metres on a variety of surfaces. Data logging and visual measurements will be made to determine the success or otherwise of the control system.

### Acceptance Criteria

- Robot will track heading to within 0.5 degree with no more than 5 degree overshoot.

# Health, Safety, Environmental, Sustainability and Ethical Considerations

## Risk Assessments

Under the broad heading of ‘constructing a robot’ come many steps and sub systems that pose a risk to health, safety and the environment.

### Power sources – Lead Acid Batteries

Lead-acid batteries (car batteries) are designed to provide a high energy, low impedance power source suitable for starting a car. They are chosen for this project because of their low cost, high energy storage suitable for the 250W drive motor and steering actuator.

Lead – acid batteries produce hydrogen during charging and discharging. Their low impedance also delivers very high fault currents, capable of starting a fire, causing the battery to explode and potentially injuring humans nearby. The following risk assessment summarises these risks and explains how the risks are minimised.

<b>‘Breakdown Event’</b>	<b>Likelihood of ‘breakdown’ occurring</b>	<b>Consequences of ‘breakdown’</b>	<b>Risk Rating before controls</b>	<b>Controls to be implemented</b>	<b>Risk Rating After Controls</b>
Explosion of hydrogen gas	Low – H2 concentration must be at combustion levels	High – acid released, energy released	Medium	Battery to be situated in a vented box away from switching contacts and electronic devices. Battery charging to take place in well ventilated area only.	Insignificant
Battery short circuit	Medium – with fairly complex power distribution, and power electronic switching, short circuits may occur	High – potential for fire, battery explosion	High	Cabling to be large enough to carry maximum robot demand only to limit fault currents. Fuse or fusible link to be at battery terminal. Power distribution and power electronics to be designed to be fail-safe (ie. not causing a short circuit).	Low

## Construction

Construction involves the modification of the metallic structure of the ‘garden cart’, involving welding, drilling, grinding, painting and lathe use. Construction of the electronic sub-systems will involve soldering and drilling operations. The risks associated with these activities and their control methods are summarised below.

### Welding

<b>‘Breakdown Event’</b>	<b>Likelihood of ‘breakdown’ occurring</b>	<b>Consequences of ‘breakdown’</b>	<b>Risk Rating before controls</b>	<b>Controls to be implemented</b>	<b>Risk Rating After Controls</b>
Burns from hot weld splatter	High – electric arc welding produces hot sprays of ‘slag’	Medium – small and possibly deep burns to skin may result	Medium	Flame-retardant welding suit to be worn while welding and face shield to be serviceable and worn correctly.	Low
Fire from hot weld	Low – combustible materials need to be nearby	Medium – potential for fire outbreak	Medium	Combustible materials to be removed from area before welding.	Low
Burns to skin and eyes from high intensity UV source	Medium- welding ‘flash’ to eyes can happen if face mask is not correctly in position	High – long term vision impairment if ‘flash’ is severe	High	Approved face mask in good condition to be worn correctly and tinted shields to be down at all times electrode is near the work piece. Long sleeved flame retardant shirt and long trousers to be worn.	Low

### Drilling

<b>‘Breakdown Event’</b>	<b>Likelihood of ‘breakdown’ occurring</b>	<b>Consequences of ‘breakdown’</b>	<b>Risk Rating before controls</b>	<b>Controls to be implemented</b>	<b>Risk Rating After Controls</b>
Burns from hot weld splatter	High – electric arc welding produces hot sprays of ‘slag’	Medium – small and possibly deep burns to skin may result	Medium	Flame-retardant welding suit to be worn while welding and face shield to be serviceable and worn correctly.	Low
Fire from hot weld	Low – combustible materials need to be nearby	Medium – potential for fire outbreak	Medium	Combustible materials to be removed from area before welding.	Low
Burns to skin and eyes from high intensity UV source	Medium- welding ‘flash’ to eyes can happen if face mask is not correctly in position	High – long term vision impairment if ‘flash’ is severe	High	Approved face mask in good condition to be worn correctly and tinted shields to be down at all times electrode is near the work piece. Long sleeved flame retardant shirt and long trousers to be worn.	Low

### Grinding

<b>'Breakdown Event'</b>	<b>Likelihood of 'breakdown' occurring</b>	<b>Consequences of 'breakdown'</b>	<b>Risk Rating before controls</b>	<b>Controls to be implemented</b>	<b>Risk Rating After Controls</b>
Burns from hot metal sparks	Low – sparks cool quickly	Medium – small burns to skin may result	Medium	Ensure operator not standing in the path of sparks discharged from grinder. Ensure others cannot stray into the path of sparks.	Low
Fire from hot metal sparks	Low – combustible materials need to be nearby	Medium – potential for fire outbreak	Medium	Combustible materials to be removed from area before grinding.	Low
Abrasive wheel shattering	Low – abrasive wheels are designed to resist shattering.	High – high speed impact of abrasive wheels can cause severe injuries	Medium	Approved face shield in good condition to be worn correctly. Long sleeved flame retardant shirt and long trousers to be worn. Inspect wheel for structural integrity before grinding. If abrasive wheel appears 'jammed' with material (ie. aluminium) replace the wheel before starting.	Low

### Painting

<b>'Breakdown Event'</b>	<b>Likelihood of 'breakdown' occurring</b>	<b>Consequences of 'breakdown'</b>	<b>Risk Rating before controls</b>	<b>Controls to be implemented</b>	<b>Risk Rating After Controls</b>
Inhalation of fumes	Medium	Medium – short term dizziness may occur. Long term effects have been documented	Medium	Use spray paint in open, well ventilated location, preferably where a gentle breeze is present. Wear a P2 organic filter mask while spraying.	Low
Pint spray in eyes	Medium	High – painful eye injury may occur	Medium	Wear goggles, keep face well away from work, if there is a breeze, stay up wind of work area.	Low

### Lathe Use

<b>'Breakdown Event'</b>	<b>Likelihood of 'breakdown' occurring</b>	<b>Consequences of 'breakdown'</b>	<b>Risk Rating before controls</b>	<b>Controls to be implemented</b>	<b>Risk Rating After Controls</b>
Metal / Nylon pieces shearing from work piece embedding in eye	Medium – a lot of high velocity material leaves work piece during lathe operation	High – potential for permanent eye injury	Medium	Wear goggles, keep face away from work piece, ensure correct turning technique is being used.	Low
Clothing caught in rotating machinery	High – operations to be carried out in winter when lots of clothing is worn	High – permanent damage to limbs	High	Ensure sleeves are rolled up securely, and all other clothing is secured, jewellery removed. Maintain clearance around rotating work piece and chuck at all times.	Low



## Soldering

<b>'Breakdown Event'</b>	<b>Likelihood of 'breakdown' occurring</b>	<b>Consequences of 'breakdown'</b>	<b>Risk Rating before controls</b>	<b>Controls to be implemented</b>	<b>Risk Rating After Controls</b>
Inhaling burning flux fumes	High – fumes are released for every solder joint, and face is usually above PCB being soldered.	Low – long term effects may occur	Medium	Keep face away from work piece when soldering. Use an extraction fan to remove soldering flux fumes.	Low
Burns from soldering iron	Low	Medium – deep burn to skin is possible	Medium	Return soldering iron to holder after each soldering operation. Switch soldering iron off after use.	Low
Eye damage from component lead trimming	Medium – component lead trimming generally results in component leads leaving the PCB at high velocity	Medium – eye injury	Medium	When trimming leads, point the work piece away from yourself and others, usually down, or secure the component lead with pliers in one hand while trimming with the cutters in the other hand.	Low

## Testing

<b>'Breakdown Event'</b>	<b>Likelihood of 'breakdown' occurring</b>	<b>Consequences of 'breakdown'</b>	<b>Risk Rating before controls</b>	<b>Controls to be implemented</b>	<b>Risk Rating After Controls</b>
'Runaway' vehicle	Medium	Medium – may cause damage to people or property	Medium	Vehicle speed to be mechanically limited through high gear ratios. Test area to be chosen away from roads and populated areas. Emergency stop button on top of robot. Bumpers wired to stop the robot if contact is made with an object.	Low
Muscle strain from lifting robot	High – robot will be heavy due to construction and power source.	Medium – back / muscle strain.	Medium	Robot to be transported using low loading trailer. Robot to be lifted using two people. If robot is heavier than 40kg, then ramps for the trailer will be required for robot to 'drive' up.	Low

## Sustainability

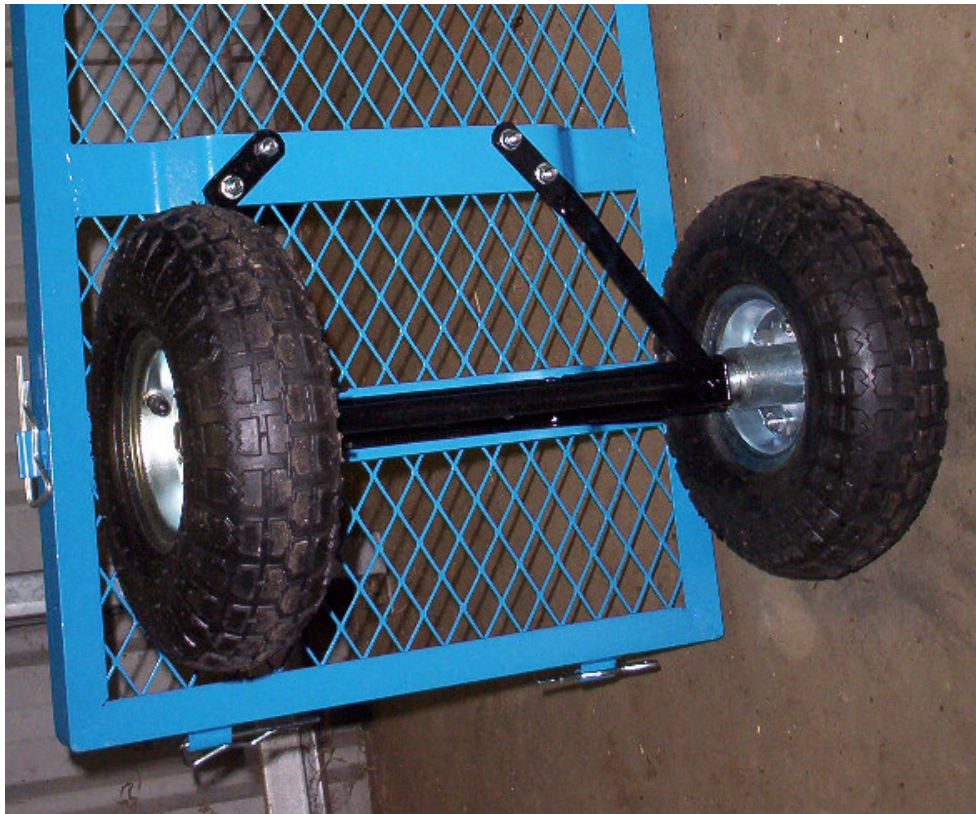
This project is being built in modular form, allowing re use of various modules should design changes occur, avoiding wastage of materials. Batteries and PCB's containing lead will be disposed of through metals recyclers. The 'garden cart' hardware will remain relatively unchanged, thus enabling it to function as a garden cart after actuators, sensors, power sources and control circuitry is removed.

## Mechanical Design

The objectives of the mechanical design are to provide a robust base capable of travel over ‘rough’ terrain to enable the testing of the vehicle in a rural environment. The chosen platform was a ‘garden cart’ kit utilising pneumatic wheels and ‘car like’ steering.

### Drive Design

Drive design and construction was a major part of the mechanical construction, as the entire rear axle had to be rebuilt around a drive shaft mounted on transmission bearings.

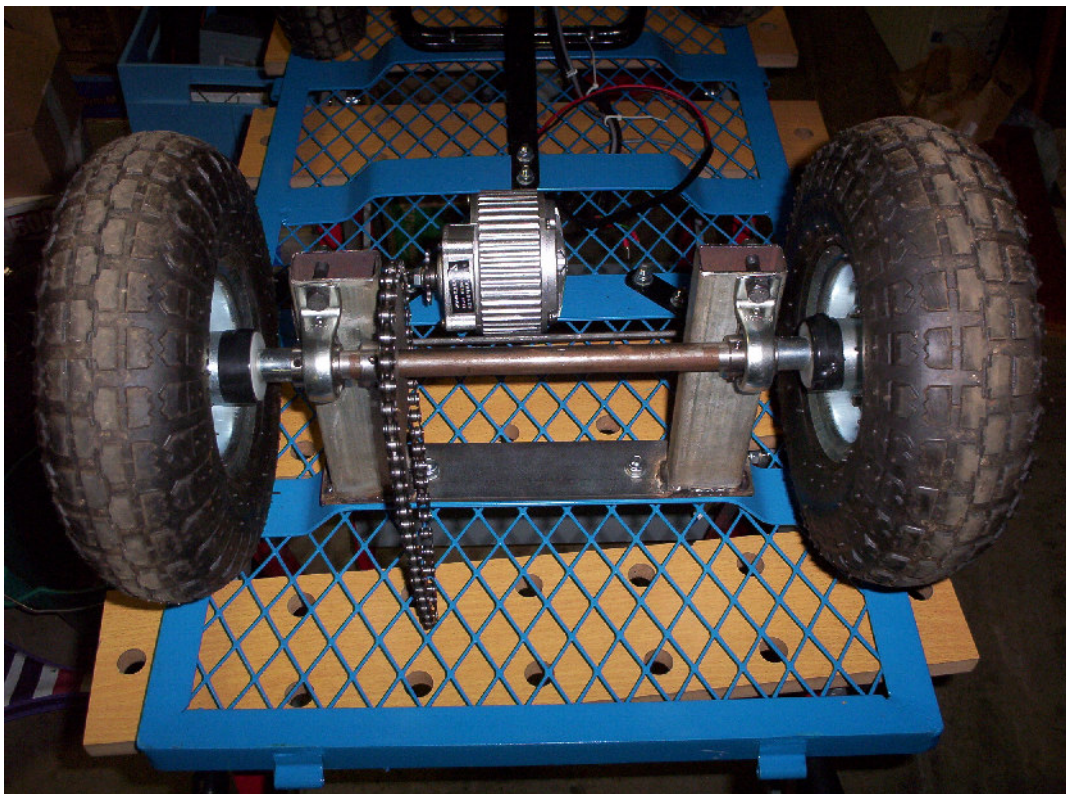


*Figure 33 – Cart rear axle before modification*

The production of the rear drive shaft design involved the following steps:

- Removal of the ‘standard’ garden cart axle and supports
- Production of a solid support to hold the bearing casings

- Production of a bracket suitable to hold the 250W drive motor
- The drive shaft had to be turned down in a lathe to enable it to fit into the ‘transmission’ bearings.
- The bearings in the rear wheels had to be removed, and solid nylon blocks were manufactured to take the place of the bearings
- A drive sprocket with correct tooth pitch and 27 teeth was purchased. This gave a chain drive reduction of 3:1. The tooth width was too wide however for the drive chain matching the motor output sprocket, so the drive shaft sprocket had to be machined to reduce its width. The centre of the sprocket was also bored out to the drive shaft diameter; two locking grub screws were installed at 90 degrees to hold the drive sprocket in place.
- Locking pin holes were drilled through the wheel hub, nylon block and drive shaft to enable locking pins to be installed, preventing slip between the drive shaft and the wheel hubs.



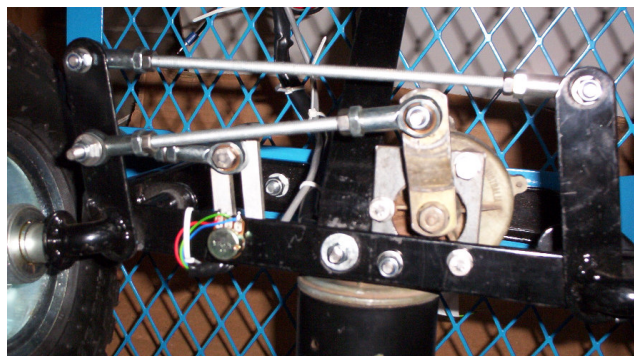
*Figure 34 – Cart rear drive after modification*

## Steering Design

The steering design requires an actuator to be attached to the steering mechanism of the garden cart to enable actuation of the front wheels.

The steps in this implementation were:

- Tighten standard steering system using ball joints. The existing steering had over three degrees of movement between each wheel, which was unacceptable for this project. Removing the standard connecting rod and installing a connecting rod with ball joints on each end rectified this. This reduced movement between each steering wheel forward angle to an undetectable level.
- Build bracket for mounting of windscreen wiper motor onto the front steering support. This bracket was manufactured from 5mm thick steel plate, drilled to accommodate the actuators output shaft bearing housing, and with mounting holes matching the actuators existing 6mm mounting screw holes.
- Ball joints and 6mm threaded rod connect the actuator output shaft to the midpoint of the steering arm, maintaining steering geometry (thus keeping a 1:1 ratio between actuator angle and steering angle throughout the steering range)
- Mount position feedback components. A basic 10k linear potentiometer was mounted on the steering support. An arm was manufactured out of 5mm aluminium plate to enable connection of ball joint rod to the feedback pot. The other end of the feedback connection rod connects to the steering arm, maintaining a 1:1 ratio throughout the steering range.



*Figure 35- Steering mechanism after modifications*

## Electrical Design

The Electrical design had to incorporate the high power H-Bridge drive requirements as well as regulated 5VDC for the microcontroller, compass module and the logic on board the H-Bridge drive module. This was provided from a 17Ahr 12V sealed lead acid battery, with power distributed from a fuse block. The supply went direct to the H-Bridge power MOSFET's via 1.5mm<sup>2</sup> cable and a 15 Amp fuse. The 5V logic supply is provided via a 78L05 voltage regulator and filtering capacitors to filter the switching noise from the H-bridge circuit.

A laptop PC is carried on the robot for use as a data logger. The PICAXE microcontroller outputs serial data each processing cycle for the data logger to read via the serial port. This information is then imported to a spreadsheet for performance analysis and graphing (see commissioning and field trials for examples)

The electrical schematic follows over the page.



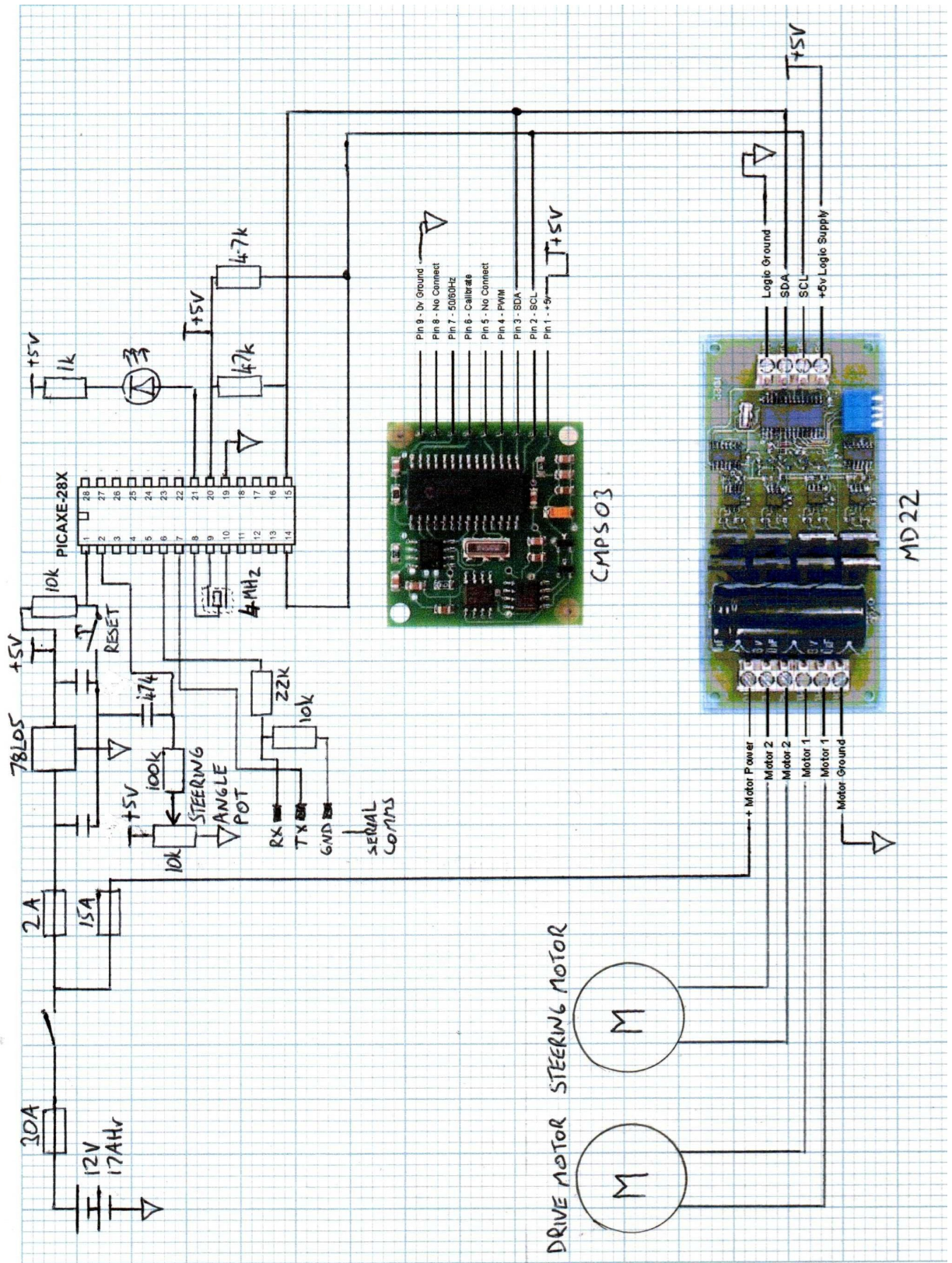
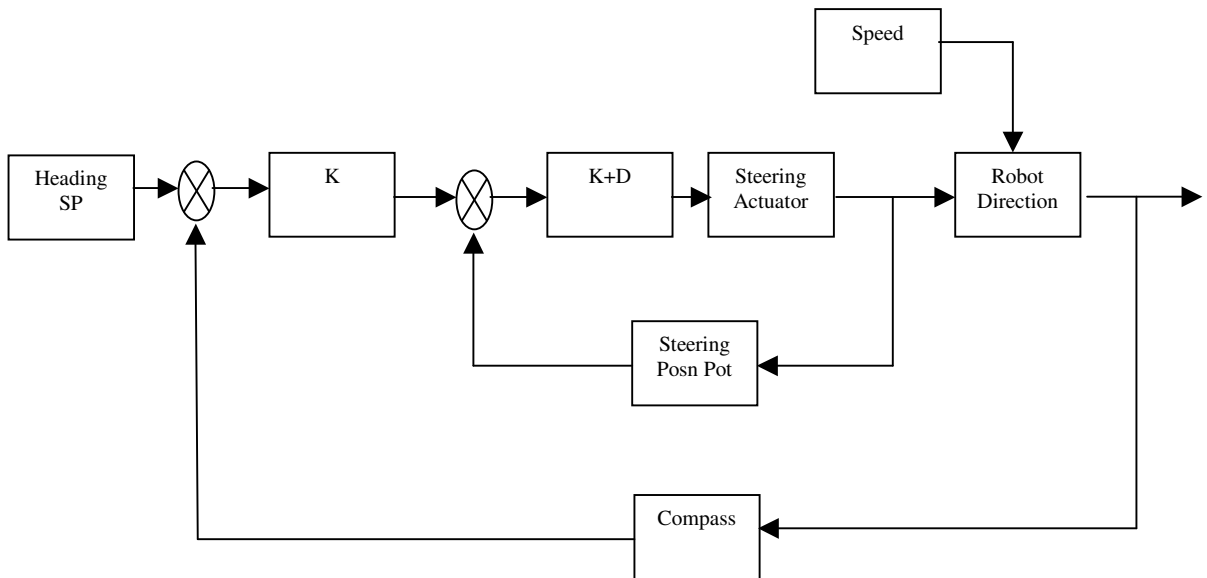


Figure 36 – Robot electrical schematic

## Software Design

The software for the robot implements two cascaded control loops and sequencing for the robot test headings.

The robot heading control was implemented through the following control loop, with the heading setpoint provided from a sequence of setpoints, changing at a fixed time.



*Figure 37 – Cascaded control loop as implemented in software*

The microcontroller is to also control the I<sup>2</sup>C drive motor interface to control the robot's forward and reverse velocity.

Register Address	Name	Read/Write	Description
0	Mode	R/W	Mode of operation (see below)
1	Speed1	R/W	Left motor speed (mode 0,1) or speed (mode 2,3)
2	Speed2/Turn	R/W	Right motor speed (mode 0,1) or turn (mode 2,3)
3	Acceleration	R/W	Acceleration for i2c (mode 0,1)
4	Unused	Read only	Read as zero
5	Unused	Read only	Read as zero
6	Unused	Read only	Read as zero
7	Software Revision	Read only	Software Revision Number

Figure 38 – MD22 I<sup>2</sup>C control registers (Source: [www.robotparts.com.au](http://www.robotparts.com.au))

The software was coded into the PICAXE microcontroller using PICAXE Programming Editor 4.1.9, programming using BASIC language as it applies to the PICAXE 28X microcontroller.

PICAXE microcontrollers do not implement floating-point variables. This presented a problem with error calculations when the control loop was being implemented in software, there being no expressions for negative numbers. This problem was addressed by creating a test to see if the error was positive or negative, then branching the program so the error and control block implementations could be handled with positive numbers.

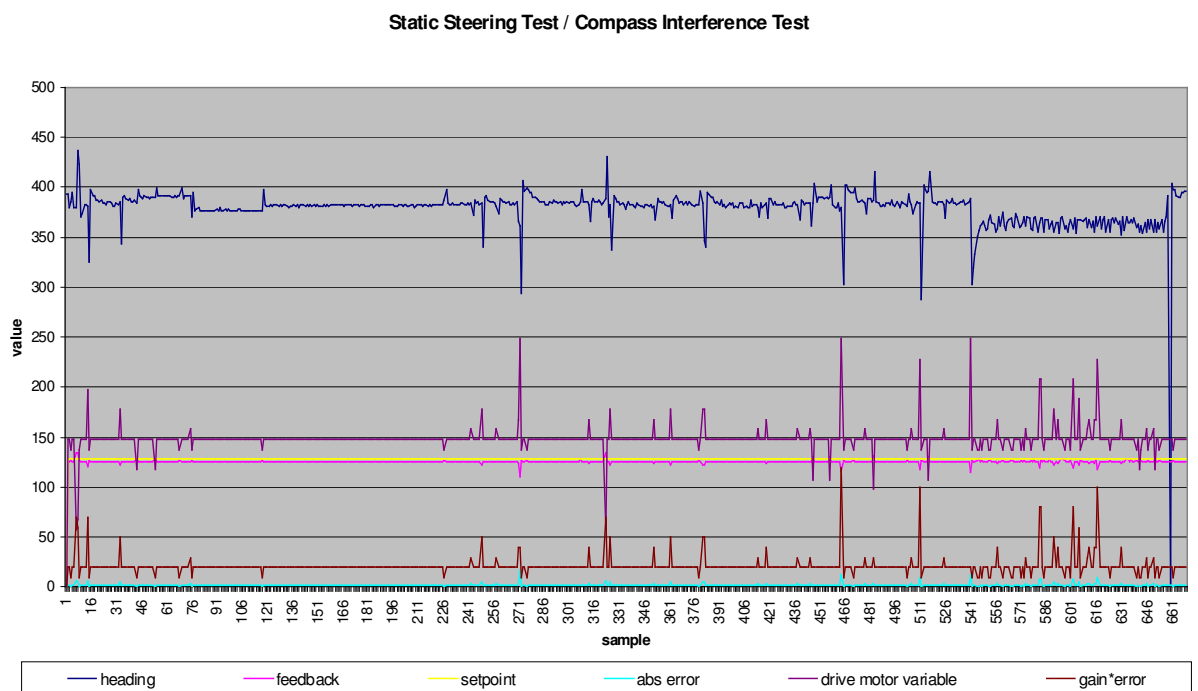
Another problem that had to be avoided with the microcontroller programming was register overflow. This is where a value of greater than 256 is entered into a register. The result of this is simply a loss of the MSB, eg. 257 will be read back as 1. This situation can easily occur in control loops where a calculation like “b2 = error \* gain” if the error is large. To prevent this problem, the error value was limited to 256/gain. This enabled full controllability around the setpoint, while preventing overflow of the register.

The software listing can be found in Appendix B.



## Commissioning

Data logging was the first system to be commissioned. A steering setpoint of 128 (1/2 travel, or straight ahead) was programmed in to the microcontroller, the drive motor was disabled and the system was started with the data logging PC running. Six straight traces on the chart was the expected result. The actual result showed a large amount of activity:



*Figure 39 – Static steering test*

Analysis of this test revealed some ‘noise’ on the steering feedback input without any actual steering mechanism movement. It was found the magnitude of this ‘noise’ was up to 2 on the 0 to 256 analog input. This was causing the steering actuator to be energised to attempt to reposition the steering.

The source of the noise was tracked to the position feedback pot. Despite a constant 5.00 volts across the pot, the output was sporadically varying by 0.01 volts. A simple way of tackling this problem was to put a simple R-C filter on the

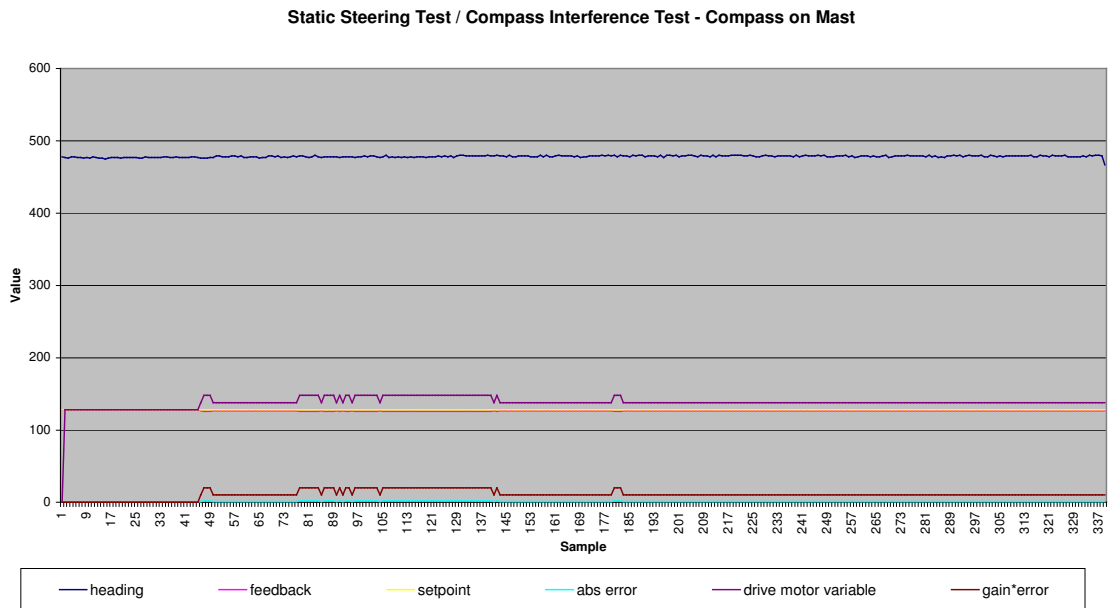
analog input to smooth this noise. A low pass point of 30Hz was decided upon, which is  $\frac{1}{2}$  the estimated sample rate of the microcontroller.

A side effect noticed during this test is that although the robot was stationary, the 'heading' value was changing regularly by up to 10 degrees (the heading value is expressed on a scale of 0 to 3600 being 0 to 360 degrees). These heading spikes correlate directly with the steering drive motor variable, and hence the energisation of the motor. For the compass control to be effective this interference had to be eliminated. Increasing the distance between the motors and the compass was attempted with the installation of an 850mm high PVC mounting mast and the results noted.



*Figure 40 – The 850mm PVC mast to hold compass clear of interference.*

The chart of results of the test with the compass mounted on the mast and with the 30Hz low-pass-filter on the steering input:

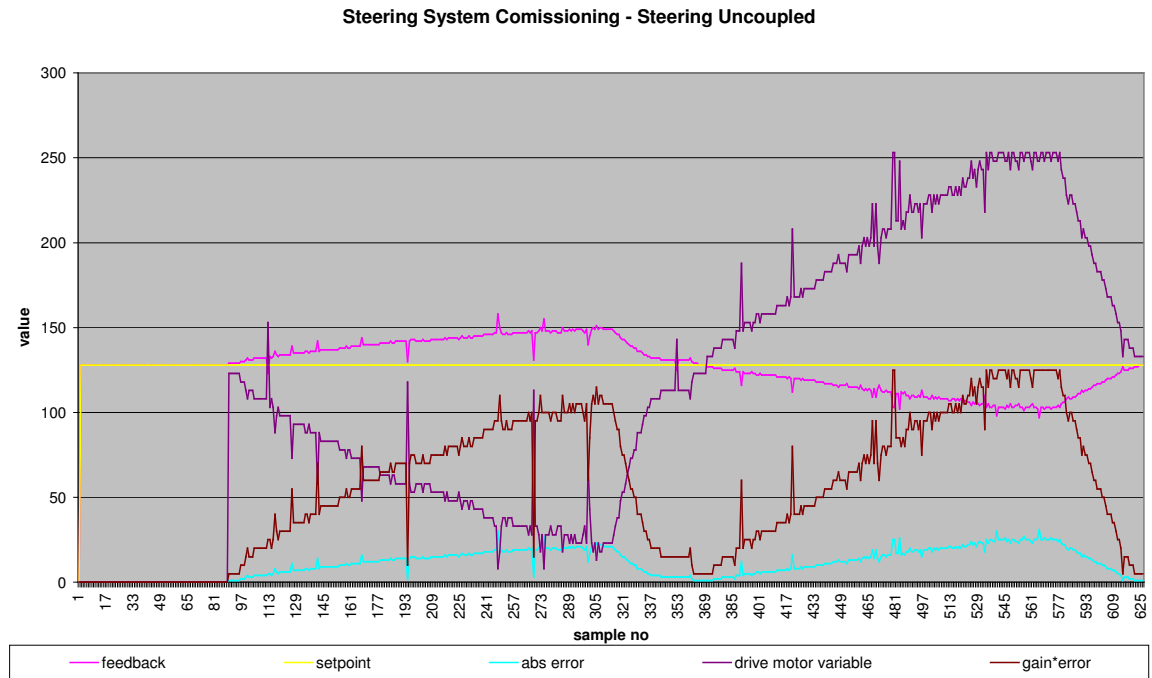


*Figure 41 – Static steering test with compass on 850mm PVC mast*

The ‘noise’ on the steering feedback was manually induced to promote steering actuator movement to assess the level of interference of the compass on the 850mm high mast. An assessment of the numerical results shows ‘ambient’ noise of the compass in my workshop as +/- 0.2 degrees, which has no correlation between the motor energising and the heading error. Thus, the mounting of the compass on a mast and the addition of the low pass filter to the steering input was successful.

### Steering Loop Commissioning

The first tests of the software was to run the system with the steering uncoupled from the actuator, to ensure the system runs as expected. This data is on the following chart:



*Figure 42 – Steering commissioning – steering actuator uncoupled*

The actual steering position was manually varied from the setpoint, and the steering actuator direction noted to ensure it was driving in the correct direction to correct the error. The output to the I2C H-Bridge was going from full forward (255) to full reverse (0). After these parameters were checked, the link from steering to actuator was installed to close the loop.

Simple step response tests were carried out by starting the microcontroller with a steering error, and assessing the response of the system via the steering feedback pot. The chart of the response obtained is shown below. The speed of the response was good and overshoot was at an acceptable level.

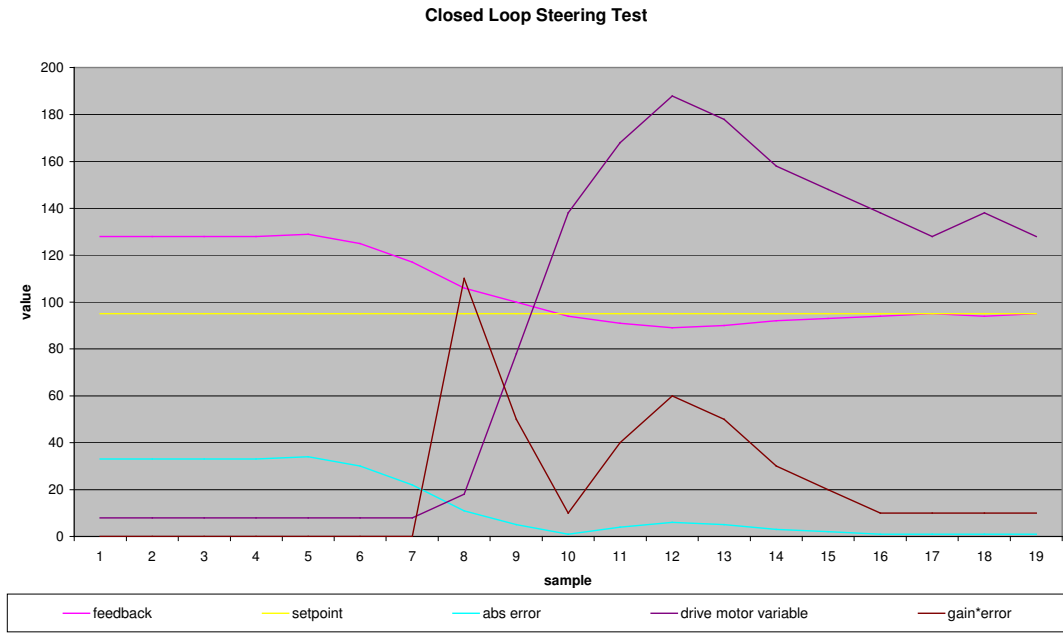


Figure 43 - Steering closed loop test

The friction of the wheels on the concrete surface provided dampening for the system. If the wheels are lifted above the surface, then an unstable response is obtained, as illustrated in the following commissioning exercise, where a triangle wave was used as the steering setpoint. A stable response was obtained when the wheels were in contact with the ground. On the 5<sup>th</sup> cycle, the wheels were lifted off the ground, and the result was instability, as can be seen below.

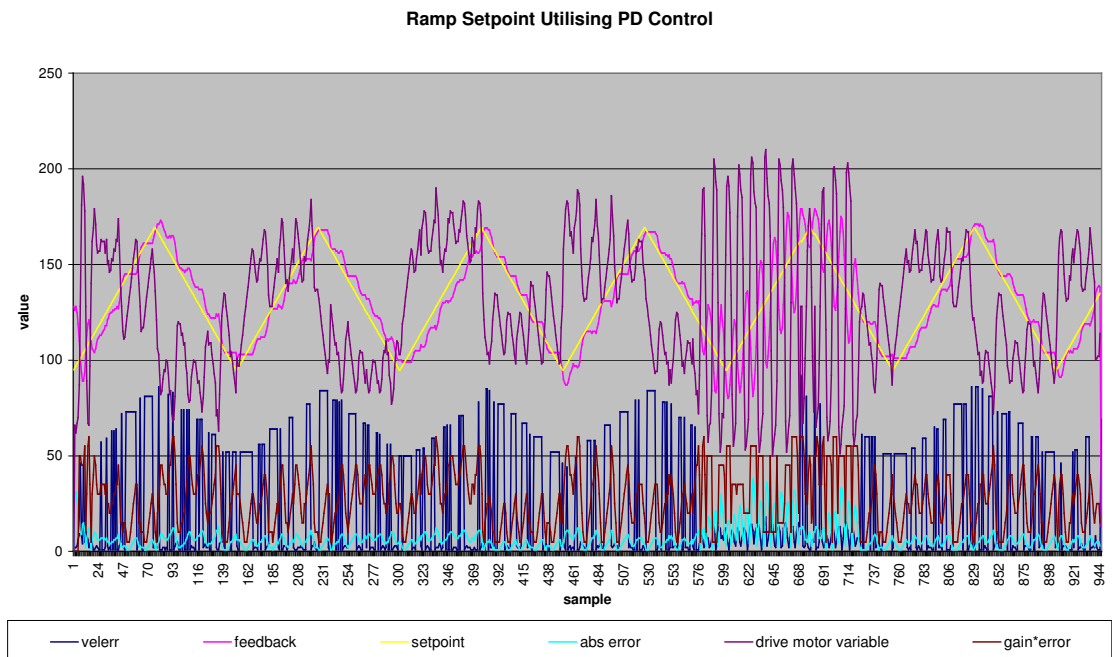


Figure 44 - Steering closed loop test with ramping setpoint

An attempt to counter this instability was made by adding a ‘derivative’ negative feedback, simply by tracking the rate of change from one microcontroller cycle to the next. It can be seen in the chart above that the velocity error value is quite active, but ineffectual at preventing the oscillations when the wheels aren’t damped by the friction with ground.

It was decided at this point that because the steering wheels should always be in contact with a surface providing enough damping for stability, the instability issue with the steering control loop raised was not a real problem.

Commissioning of the drive motor was achieved by sending a drive signal to the I2C H-Bridge:

drivemotors:

```
i2cslave $B0,i2cfast,i2cbyte      ' Define i2c slave address for the
MD22
writei2c 1,(b8)                   'steering motor speed / direction
writei2c 2,(168)                   'drive motor speed / direction
```

The ‘writei2c 2,(168)’ command sends the value of 168 to the H-bridge drive to motor control channel 2. 128 sends a ‘stop command’ while 255 is full forward and 0 is a full reverse command. Intermediate values represent a pulse-width modulated proportional drive to the motor, to control speed. The motor was observed to run in the correct direction, and as such, the drive motor commissioning was completed.

## Chapter 4 – System Analysis

## Field Trials

The aim of the first field trial was to assess:

- mechanical construction
- power electronics
- directional control (outer compass control loop)

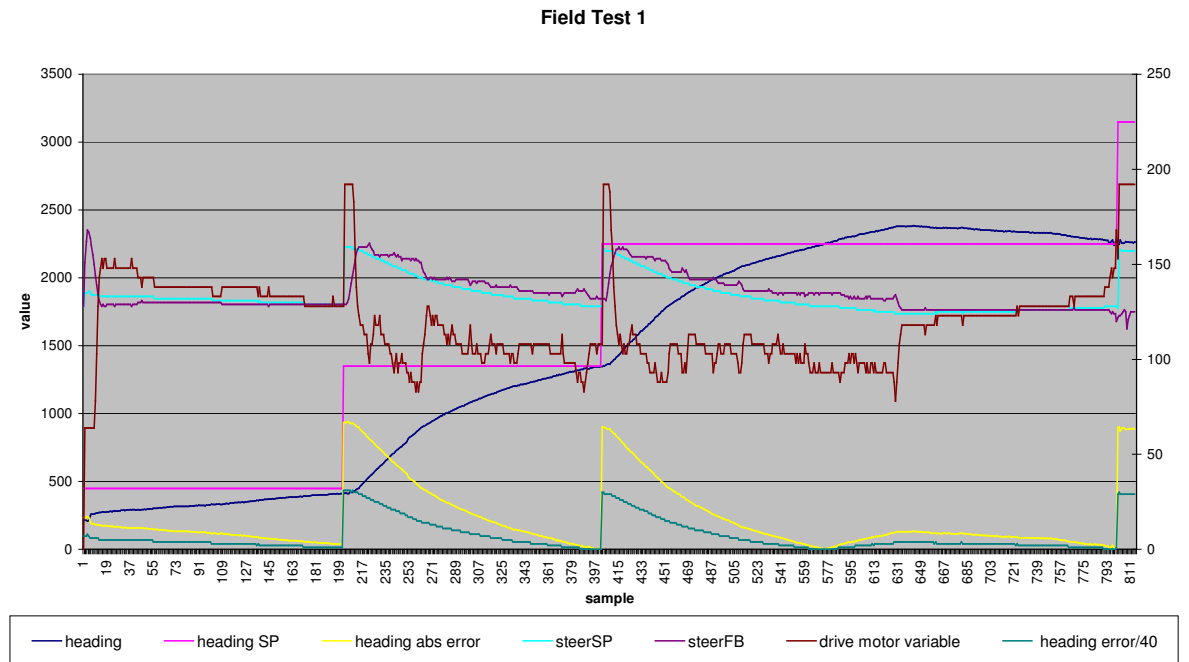
A rural property was chosen for the trial, as discussed in the aims and objectives of chapter 1. The microcontroller was programmed to follow the following sequence

1. Pause for one second during power up.
2. track heading 450 (45 degrees or North-East) for 200 microcontroller cycles at 98% speed.
3. track heading 1350 (135 degrees or South-East) for 200 microcontroller cycles at 98% speed.
4. track heading 2250 (225 degrees or South-West) for 200 microcontroller cycles at 98% speed.
5. track heading 3150 (315 degrees or North-West) for 200 microcontroller cycles at 98% speed.
6. stop

The first trial run uncovered a mechanical fault. The drive chain was dislodging from the drive shaft sprocket. This was later repaired by adding large ‘hose clamps’ to help secure the drive motor body to prevent the drive motor twisting under torque and dislodging the chain.

A plot of the results of the first trial run can be seen below. Watching the robot during the trial, it appeared to make fairly sharp turns at each change of heading, and then appeared to track the heading until the next setpoint was reached. An analysis of the data showed this wasn’t the case, with a ‘sluggish’ response to each new setpoint. This was due to the fairly low gain on the ‘outer’ compass control loop. The ‘inner’ steering control loop functioned as expected.





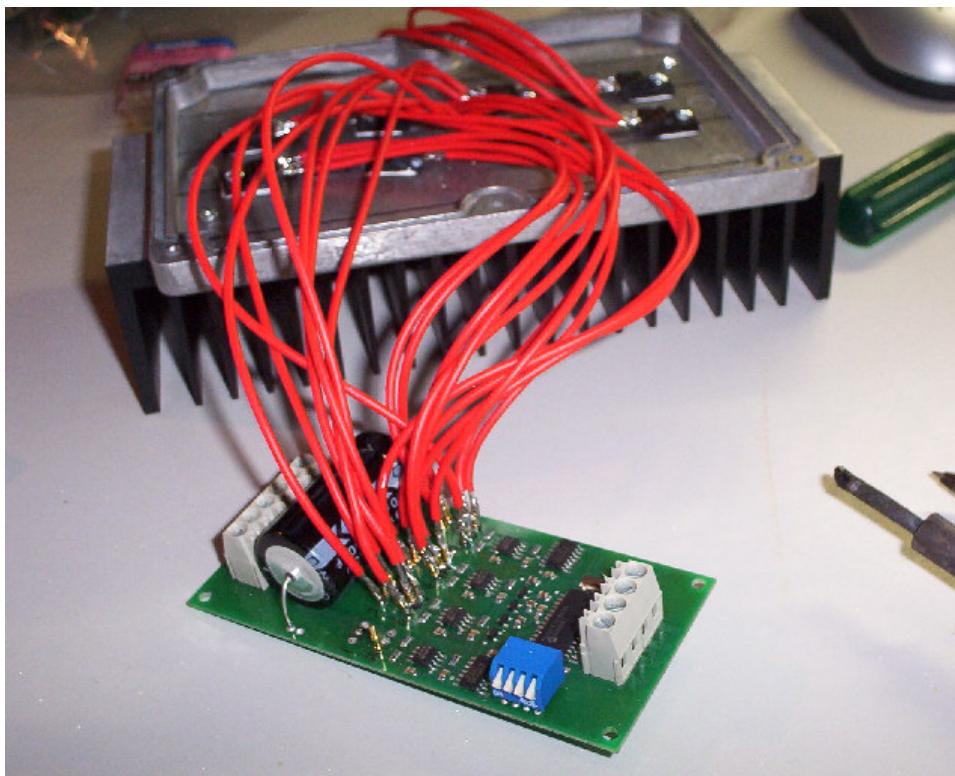
*Figure 45 – First field trial results*

After a few more runs through this sequence, a fault developed where the steering would go to maximum right hand lock and stay there regardless of the microcontroller instructions for the robot to do otherwise. This fault was traced to one of the MOSFET's in the MD22 H-bridge drive overheating, and entering a mode where it fully conducts regardless of the gate voltage.

## Improvements resulting from field trial

The following improvements were made following the first field trial:

- A large heatsink was then installed onto a cast aluminium case, and the MOSFETS removed from the MD22 PCB and placed on the heatsink.
- Extra hose clamps added to around the drive motor body to secure it against twisting when driving.
- The 'outer' heading compass control loop had its gain increased to make the turning action less sluggish, and reduce steady-state error.



*Figure 46 – Placing of MOSFETs onto heavy duty heatsink*

Further field trials were then attempted. The results of these trials were:

- The robot no longer exhibited the 'lock-up' of the steering due to the addition of the power heatsink.
- The drive motor did not 'twist' in it's housing, preventing the chain from falling off

- Responsiveness was improved due to an increase in the outer loop heading gain. Previously the heading error was divided by 30 to give the proportional control to the steering loop. After some experimentation, this figure was reduced to 4. Theoretically, this should result in a steady state error of less than 0.4 degrees.
- A problem developed with data logging, despite having an identical hardware set-up as used in the initial field trial. After a few initial runs without data logging (observing the performance of the robot visually), the data logging laptop was added. This appeared to cause the microcontroller to reboot on a regular basis. Swapping of laptops was tried with no change in the fault, as well as removing the RX data line from the microcontroller to ensure the laptop was not sending data. With the data logging laptop removed, the robot resumed normal operation. Further investigation into power supply loading is required.

Further investigation is required to remedy this fault, and due to time constraints will not be included in this dissertation.

## Chapter 5 - Future Work

This Chapter details some improvements that may be made to this project in the future.

### Improvements to microcontroller speed and ability

To improve the speed of the microcontroller, it is possible to place RS232 serial communications into a separate microcontroller, interfaced to the main microcontroller via the I<sup>2</sup>C bus. This then takes the slow task of outputting the serial data for data logging at 4800 bits per second and instead transfers the same data at 400 000 bits per second. This option will lead to the build up of data in the second microcontroller as the data will be coming into it much faster than the data output via the serial cable to the PC. A possible remedy for this would be to only transmit data every 10 or 20 microcontroller cycles.

Another approach is to connect an I2C EEPROM directly to the I2C bus for data logging. EEPROMs are available up to 1M bits in size, offering 128K bytes of storage in a single 8-pin device. As most of the field and commissioning trials produced around 50k bytes of data, a single 1M bit EEPROM would be enough to store the short journey's information.

A more advanced processor could be used, such as a Motorola HC12, 'embedded' Intel processor or similar. Another option is to make a windows or Linux PC the primary controller. This will add a lot of ability, and make the implementation of GPS input easier, but also remove the 'ruggedness' of an embedded processor / controller solution.

## Compass tilt error compensation

As shown in the research for this project, compass tilt error compensation is essential for satisfactory performance of the heading control loop. This can be achieved in several ways:

1. Utilize a 3-axis electronic compass. These claim to deliver accurate heading direction regardless of horizontal plane tilt, but attract a price premium of over ten times the purchase price of the 2-axis compass unit.
2. Place the compass in a mechanical gimbal to keep the 2-axis compass in the horizontal plane. This could be a cheaper option than (1) above, but the mechanical parts will wear over time, and the gimbal will have a mechanical resonance that will require dampening. The time constant of the mechanical damped gimbal will have to be known to allow for appropriate lag filtering to the controller in case of a step change in tilt.

## Improvements to steering actuator

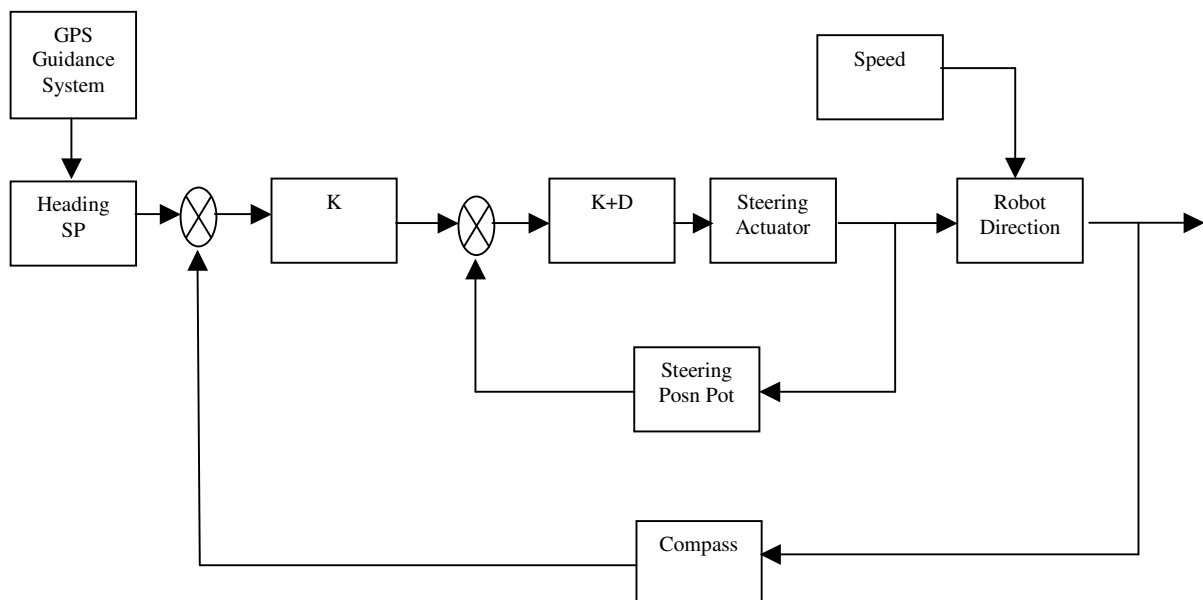
The windscreen motor drive has gearing too high for this application using a simple proportional + derivative controller for steering position. A more advanced control algorithm, perhaps with tachometer feedback on the motor shaft, may be able to control the windscreen wiper motor more effectively.

Another option is to replace the windscreen wiper motor with a linear actuator with a slew rate suitable for this application and a low inertia to enable proportional only, high gain control of the steering system.

## GPS

As stated in the introduction, the electronic compass heading control system has been built to receive heading corrections from a GPS based navigation system. This essentially creates another higher level in the cascaded loop providing heading update information to the heading control loop. Control over vehicle speed would also be implemented through this system.

The advantages of this system over a GPS control system without the electronic compass control loop is that heading control is maintained while the GPS is updating it's information and also when the system does not have a satellite lock. Naturally in the latter situation, a decision must be made as to how long the system should follow it's heading without a satellite lock, and also how many satellites must be available before the robot stops following the heading and waits for the required number of satellites to come into view.



*Figure 47 – Control loop showing GPS heading update input*

## Machine Vision Systems

A similar heading update system could be developed with machine vision applications. For example, if tracking the vanishing point of a row of crops using machine vision, the error determined by the machine vision system could be passed to the heading control system as an increment up or down value, integrating out the error in heading.

## Chapter 6 – Summary

This chapter summarises the results and conclusions of this project in Mobile Robot Guidance and Navigation.

The performance criteria could not be fully assessed due to the serial communications problem in the last weeks of the project timeframe. Performance criteria that were addressed were:

- Static drift test – electronic compass was within tolerance of less than 0.4 degrees per minute.
- Step response test – better than 270 degrees per minute was measured (90 degrees in 1/3 minute)
- Noise was less than 0.2 degrees between any two consecutive heading samples.
- Robot heading test – the initial field test failed to meet the 0.5 degree accuracy in heading criteria. After modifications to the heading control loop gain, in theory, the robot should now have a maximum heading error of 0.4 degrees, within the acceptance criteria. This has not been proven in practice at this stage.

Generally, the electronic compass has proven to be a reliable device with high resolution. It is very sensitive to tilt errors, and this will need compensating in a ‘practical’ implementation.

The environment surrounding the compass is of prime importance. As demonstrated in this project, a rural environment provides an ideal place to implement the electronic compass sensing, due to the ‘quiet’ magnetic environment. However, implementation in industrial or even modern domestic environments may be impossible.

When used in a suitable environment, and with tilt compensation, the electronic compass makes an ideal high speed ‘inner’ loop controller. It is able to quickly



identify heading changes enabling the controller to make rapid corrections. Provided that errors are compensated for or at least detected, the electronic compass provides a robust solution for the application of sub second heading control.

It is doubtful that the electronic compass would ever be used as the sole overall heading / position sensor in a robot navigation system. Instead, it would be used as a 'inner' loop controller as in this project, or as part of 'sensor fusion' with other sensors such as GPS, machine vision, radar, ultrasonics, laser scanners, accelerometers or gyroscopes, through a Kalman filter.

## Appendix A – Project Specification

University of Southern Queensland  
Faculty of Engineering and Surveying

**ENG4111/2 - Research Project  
PROJECT SPECIFICATION**

FOR: **Leslie Heath AIRS**  
TOPIC: 05-047, Mobile Robot Guidance and Navigation  
SUPERVISOR: Dr. John Billingsley

ENROLMENT: ENG4111 – S1, X, 2005  
ENG4112 – S2, X, 2005

SPONSORSHIP: Faculty of Engineering and Surveying

PROJECT AIM:

- (1) Research, model and implement electronic compass sensing into the load-haul dump truck system developed at USQ, with the aim of improving the control action.
- (2) Researching an effective radio - telemetry system with the aim of making the present peer differential GPS system 'cordless', enabling implementation in a rural environment.

PROGRAMME: **Issue A, 21 March 2005**

- (1) Research information on electronic compass heading sensing, it's characteristics and requirements for the implementation in a mobile system.
- (2) Research the control theory required to achieve stable control using multiple inputs into a single output system.
- (3) Define the present problems with the load haul dump truck navigation and assess suitability for the electronic compass to meet the aim of improving the control action of the load haul dump truck.
- (4) Model the electronic compass as part of the load haul dump truck navigation system. Derive algorithms for error detection.
- (5) Carry out experimental evaluation of an electronic compass module and assess it against the requirements in (1).
- (6) Implement the electronic compass in hardware on the load-haul dump truck.

As time permits

- (7) Research an effective radio - telemetry system with the aim of making the present peer differential GPS system 'cordless'.
- (8) Model and implement if possible given time and budget constraints.

AGREED: \_\_\_\_\_ Les Airs (STUDENT)

\_\_\_\_\_ Dr. John Billingsley (SUPERVISOR)

(DATED) \_\_\_\_/\_\_\_\_/\_\_\_\_

## Appendix B – Software Listing



```

moveleft:
    w6=w0-w1                                'determine direction error to left
    srtxd(#w0,"",#w1,"",#w6,"",#b6,"",#b5,"",#b8,13) 'send data to programming port
    if w6>100 then movemaxleft                'turn maximum if error > 5 degrees
    b4=w6/2                                  'scale error down b4=w6/(50/40)
    b6=128-b4                                'proportional control to left = midpoint - error to right

    if b6 < 88 then movemaxleft
    goto posnfbk

movemaxleft:
    b6 = 88
    goto posnfbk

posnfbk:
    b11=b5
    readadc 0,b5
    b12=b5/2                                'this produces a two-sample moving average for
steering posn fbk                            'this was installed to reduce effect of spikes on ADC
    b13=b11/2+b12
    b5=b13
    'pause 10
    'if b5 > 180 then stopdrive              'if feedback is outside range stop drivemotor
    'if b5 < 76 then stopdrive

steercontrol:
    if b5<b6 then steerright                 'b5 is feedback value
    if b5>b6 then steerleft
    if b5=b6 then stopdrive
    goto stopdrive

steerright:
    b7=b6-b5                                'error to left of setpoint
    if b7>12 then maxright                  'this number < 64/gain
    b9=b7*5
    b8=128+b9                                'add error to stop value to drive right
    goto drivemotors

maxright:
    b8=128+64
    goto drivemotors

steerleft:
    b7=b5-b6                                'error to right of setpoint
    if b7>12 then maxleft                   'this number < 64/gain
    b9=b7*5
    b8=128-b9
    goto drivemotors

maxleft:

```

```
b8 = 128-64
goto drivemotors
```

stopdrive:

```
b8=128
```

drivemotors:

```
i2cslave $B0,i2cfast,i2cbyte
writei2c 1,(b8)
writei2c 2,(b10)
'pause 10
```

```
' Define i2c slave address for the MD22
'steering motor speed / direction
'drive motor speed / direction
'1/100th second pause to allow i2c comms to complete
```

- delete if not necessary.

timekeeper:

```
peek $50,b12
peek $51,b13
w0=w6
w6=w0+1
poke $50,b12
poke $51,b13
if w6>1000 then turn4
if w6>800 then turn3
if w6>400 then turn2
if w6>200 then turn1
goto readcompass
```

```
'load counter values into b12:b13 (w6)
```

```
'temporary store w6 in w0
```

turn1:

```
w1=1350      'head SE
b10=250
goto readcompass
```

turn2:

```
w1=2250      'head SW
b10=250
goto readcompass
```

turn3:

```
w1=3150      'head NW
b10=250
goto readcompass
```

turn4:

```
w1=3150      'head NW &
b10=250      'stop drive
goto readcompass
```

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