DESIGN OF A LOW-COST AUTONOMOUS GUIDED CART FOR MATERIAL HANDLING

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Design of a Low-Cost Autonomous Guided Cart for Material Handling

by

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Declaration

In accordance with Rule G4.6.3, I hereby declare that this dissertation for *Masters in Engineering (Mechatronics)* to be awarded is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another university or for another qualification.

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Date: *28 November 2014*

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Nomenclature

Acronyms

AC	-	Alternating Current
AGC	-	Automated Guided Cart
AGV	-	Automated Guided Vehicle
CAD	-	Computer Aided Draw
CAN	-	Controller Area Network
CSIR	-	Council for Scientific and Industrial Research
DC	-	Direct Current
FBD	-	Function Block Diagrams
GA	-	General Assembly
GM	-	General Motors
GMSA	-	General Motors South Africa
GPS	-	Global Positioning System
I2C	-	Inter-Integrated Circuit
IEEE	-	Institute for Electronic & Electrical Engineers
IO	-	Input/Output
IR	-	Infra-Red
IP	-	Instrument Panel
IP	-	Ingress Protection
ITSDF	-	Industrial Truck Standards Development Foundation
LAN	-	Local Area Network
Li-Ion	-	Lithium Ion
LSB	-	Least Significant Bit
MTU	-	Master Terminal Unit
NIC	-	Network Interface Card
NiCd	-	Nickel Cadmium
NiMH	-	Nickel Metal-Hydride
NMMU	-	Nelson Mandela Metropolitan University
PCB	-	Printed Circuit Board
PHP	-	PHP: Hypertext Preprocessor
PID	-	Proportional, Integral, Differential
PLC	-	Programmable Logic Controller
PWM	-	Pulse Width Modulation
OS	-	Operating System
RFID	-	Radio Frequency IDentification
RPM	-	Revolutions Per Minute
RTE	-	Run-Time Environment

RTU	-	Remote Terminal unit
RX	-	Reception
SANS	-	South African National Standards
SBC	-	Single Board Computer
SCADA	-	Supervisory Control And Data Acquisition
SQL	-	Structured Query Language
ST	-	Structured Text
THB	-	Thai Baht
TTL	-	Transistor-Transistor Logic
TX	-	Transmission
UART	-	Universal Asynchronous Receiver/Transmitter
UAV	-	Unmanned Aerial Vehicles
US$	-	United States Dollar
WAMP	-	Windows, Apache, MySQL, PHP

Symbols

a	-	acceleration
h_t	-	tyre section height
m	-	mass
r	-	radius
v	-	Linear velocity
w	-	tyre section width
x	-	distance

C	-	Tyre Characteristic co-efficient
C	-	Capacitance
D	-	Diameter
F	-	Force
I	-	Current
N	-	Angular Velocity (RPM)
R_x	-	Rolling Resistance Force
T	-	Torque
W	-	Weight

η	-	Efficiency
μ	-	Co-efficient of Friction
ω	-	Angular velocity (rad/s)

Terms

The terms AGC and AGV are used regularly in the text. In general AGC refers to a smaller vehicle, and in most cases the product of design for this project; AGV refers to autonomous guided vehicles in general, of all sizes.

Abstract

This dissertation covers the design and manufacture of an autonomous guided cart (AGC) for use in the material handling industry. General Motors South Africa (GMSA) requires a low-cost AGC for use in their Struandale plant. A budget of R35 000 per unit was proposed.

The researcher, in collaboration with staff at GM, compiled a list of engineering requirements for the AGC. After research into the unique problems of the project, an examination of a previous design attempt by staff of GM Thailand, the researcher developed a new design, the subject of this report.

Different solutions for each design problem were investigated before the design was finalised. A three-wheeled vehicle was designed making use of two motors in a differential-drive setup to control motion. Navigation is via a line-following mechanism, using an induction sensor-array in conjunction with a pre-laid metallic strip. To aid the design, the system was modelled to understand the different control elements at play.

The researcher developed software for several aspects of the design: for the PLC controlling the system and motors; for a microcontroller that communicates with the PLC and a wireless module; for a computer server that communicates with a second wireless device, receiving information from the PLC; and a web interface to view this information. These form the SCADA integration of the project

The final product meets the GMSA specifications. It is a robot capable of towing a trolley of mass not exceeding 350 kg. While the robot is able to navigate a pre-laid route, it cannot reliably stop at marked locations. It is possible to monitor the system via a web-interface. The robot is capable of operating for an entire 8-hour shift before the batteries need to be recharged. The total cost of the prototype was R26 340.

Keywords: Autonomous guided vehicle, Low-cost design, Material handling

Chapter 1

Introduction

This dissertation covers the design, manufacturing and testing of a prototype automated guided cart (AGC). This chapter describes the motivation for the project; discusses the problems to be overcome; lists the project aims and defines the project scope. Finally, the methodology is discussed.

In Chapter Two a literature review is undertaken which covers various possible design choices for each of the identified problems, listing important points for making design decisions. Legal requirements relating to the use of automated machinery in industry are discussed; the relevant General Motors South Africa (GMSA) electronic standards which govern the use of equipment on site are listed; and a previous design completed by GM Thailand is reviewed.

Chapter Three begins by outlining the specifications required by GMSA. It continues by giving an overview of the first design step of the project. Initial decisions made concerning systems and devices to be used in solving individual design problems are canvassed. It concludes with a discussion on the quality versus price aspect of the project.

Chapter Four covers the main design decisions, component selection and system design. This includes the development of CAD models, electronic circuits and various parts of code that were necessary for the completion of the project. In addition the system was modelled in Matlab to test control methods. The chapter ends by presenting the expected performance of the device.

Chapter Five describes the processes followed when testing the unit and the results from these tests. Different tests were run to evaluate the AGC's performance with regards to different design elements.

Chapter Six discusses the test results and comments on the success of the project. Several recommendations are made for ways to improve the design for future models of the AGC and a general conclusion is drawn.

Six appendices are included after the List of References. These provide additional information covering various topics, ranging from time and cost estimates for the project to technical details relating to the wiring and source code used. A guide for setting up the SCADA system is also supplied.

1.1 Rationale and Motivation

GMSA requires additional automation in the General Assembly (GA) area for their plant in Port Elizabeth, South Africa. GMSA identified the specific topic of AGCs and made several efforts into sourcing AGCs for use in the factory.

GMSA have indicated several areas in their manufacturing plant where they felt AGCs could be implemented to aid their production processes. These generally entail the delivery of stocked trolleys to certain areas of the plant, and the return of empty trolleys back to the loading area. It was anticipated that the pickup and drop-off of the trolleys could be automated, requiring only the correct placement of the trolleys by personnel to assist the pickup-process.

GMSA has considered AGCs for several years. Local design companies were approached but, on consultation, indicated high costs associated with development. There was interest in importing redundant AGCs from GM North America, but the supply of these were limited, not necessarily designed for the specific purpose and initial cost indications exceed the budget.

GMSA also approached GM Thailand to design an AGC for them. A subsequent design was received along with a cost breakdown and manufacturing drawings. However, on review of the presentation received from GM Thailand, several inconsistencies were observed in the various design documents. Photos indicate that a prototype was built, but there was no indication whether or not it was ever put into use or tested. GMSA believed it would require excessive work to render the design operational. Furthermore the current cost breakdown indicated an amount higher than GMSA felt would be cost-effective.

Apart from GMSA's specific requirements, there was also a need in general for low-cost AGCs for commercial use. Students at the University of Waikato (in Hamilton, New Zealand) worked on the design of a low-cost (less than US$ 2 000) autonomous guided vehicle (AGV) for security applications (Carnegie *et al.*, 2004). The project had no commercial association and although low cost, several second-hand parts were used, its suitability for an industrial environment is also unknown.

Although increasingly AGVs are being used in the South African manufacturing industry, there is still a lack of local development. The only institutions that appear to be working in the industry are local universities and the CSIR (Council for Scientific and Industrial Research), which are mainly focused on safety in mining industry (Campbell, 2011). As a result of this lack of local activity, parts commonly required for the manufacture of AGVs are expensive and difficult to acquire.

Several local manufacturing companies do however make use of AGVs: Mercedes-Benz at certain stages of their assembly process, and both JendaMark and Eberspacher use AGVs for material handling (Private Communication, 2012).

In 2004 the Material Handling Industry of America estimated that for a low complexity, simple control AGC, the least one could expect to pay was US$ 50 000. Certain models could cost up to US$ 250 000 (Solomon and Wilck, 2004). Despite an increase in use, AGV prices remain high.

A recent quote for AGVs received from Creform quoted US$ 18 000 per unit, excluding shipping or import duties (Creform, 2012). The AGC was a fairly basic line-following model. Despite a lower cost than suggested by Solomon and Wilck (2004), this could still be considered too expensive for many applications, and particularly for smaller companies.

In discussion with GMSA it transpired that when considering the use of automated machinery, standard procedure is to compare the cost of equipment with the cost of employing a human to perform the same function for a year. This will vary according to prevailing socio-economic factors in the country concerned. For example, where low labour costs are involved, AGCs will be used less often. Unless the cost is lowered and the versatility is increased, human labour will continue to remain preferential in many areas.

For these reasons GMSA required an AGC design that would need only minimal human interaction, and be durable and reliable while safe to work with, thus ensuring a cost-effective product. The design also needed to meet their design criteria to ensure a working product for their application.

1.2 Problem Statement

GMSA requires AGCs to act as automated tuggers in their general assembly area. Investigations into the feasibility of such an investment had not been successful due to the high cost of individual AGCs. GMSA believed that current AGC designs could be optimised to ensure an AGC that is as capable and reliable as commercially available products but at a more reasonable cost.

To ensure that the final product conformed to the requirements of GMSA, it was necessary to develop a list of user requirements. There are many options to consider relating to the various design elements of an AGC. The main areas of research are navigation, locomotion and control.

1.2.1 Research Aims

The aim of this project is to develop a cost-effective AGC for GMSA. This will be achieved by completing the following objectives: the

1. Completion of comprehensive research on all design factors relating to the AGC, presented in the form of a Literature Review.
2. Compilation, in consultation with personnel at GMSA, of a list of user/engineering requirements to ensure the final design is suitable for its desired use.
3. Review of the AGC design compiled by GM Thailand.
4. Design of an AGC that meets the requirements set by GMSA.
5. Building of an AGC to the specifications set out in the design.
6. Development and undertaking of a set of tests to evaluate whether the AGC meets the requirements.
7. Implementation of AGCs into a SCADA interface (this includes AGC communication and localisation)

Although the last objective was not specified by GMSA, it has been included to display additional features which are commonly installed that can be achieved in a low-cost iteration.

1.3 Methodology

The main objective of the project is to have a final product capable of meeting GMSA's requirements. A substantial section of research was required to understand fully both the requirements of the project and the appropriate methods of achieving the desired results.

A list of practical requirements for the product was developed through interviews with several members of the GM staff. The design requirements were analysed, and from this several main categories of research were delineated. Earlier research on several similar projects provided valuable information and helped to focus attention on certain key areas.

The main topics of research identified were:

- Drive;
- Navigation;
- Control; and
- Sensors.

Each of these categories has various ways in which the problem can be solved and an array of resources was available for research. Many topics are covered by relevant text books, and more recent solutions were found in databases of published reports and papers. Organisations such as the Institute of Electrical and Electronic Engineers (IEEE) have several publications and catalogues of conference proceedings with papers covering modern approaches to solving certain AGC related problems.

In 2011 GMSA had requested a design for an AGC from GM Thailand. A design was developed, but failure to produce the prototype gave GMSA doubts regarding the functionality of this design. Part of the current project required the assessment of the previous design to ascertain its possible shortcomings and as an assistive tool in determining possible design solutions.

Along with the GM Thailand design, several other designs from the commercial, education and hobby industries were researched.

With a good understanding of other designs, GMSA's requirements of the project and a range of potential solutions, the design of the AGC began. Calculations were required to determine usable engineering specifications from the list of user requirements initially compiled.

From these engineering specifications, product selection could be performed. Selection included all items which needed to be purchased such as motors, controllers, sensors etc. With the major components identified, design of the physical structure (frame) could take place.

For the physical design of the AGC, CAD software, specifically Autodesk Inventor Professional , was used. A full CAD model of the AGC was developed. The assembled model included many of the additional items such as buttons and lights, which would be purchased and used as is.

From the model a full set of machine drawings was compiled. Finally, the frame was manufactured from these drawings, and specific exports for the laser cutting of certain sections.

Testing of most bought items is required to ensure correct response. Most items were tested on an individual basis where there was no dependence on the correct functioning of other components. The researcher wrote simple programs to test the functionality of control systems and the various I/O (input/output) devices.

Additional software requirements related to the programming of various aspects within the project. To program the PLC used in the project, Schneider Electric (Telemechanique) TwidoSuite was required (Schneider Electric, 2009). A microcontroller used for wireless transmission made use of the Arduino programming environment (Arduino, 2012).

The Python 2.7 RTE (Run Time Environment) was required for the compiling and testing of code written to interface the computer with a wireless terminal (Dustman, 2010). This code in turn communicates with a MySQL database. The database was run as part of the WAMP (Windows, Apache, MySQL, PHP) server software suite (Bourdon, 2012). The PHP aspect of this suite was also used for the SCADA interfacing of the database.

As more components were added to the system, continual testing took place to ensure that the new components did not negatively impact the correct functioning of the existing components.

Chapter 2

Literature Review

2.1 Autonomous Guided Vehicles

The term autonomous guided vehicle (AGV) can refer to almost any robotic body that has the ability to navigate an environment without direct human input. The applications and designs of AGVs are extremely varied, with different technologies being used to navigate and drive them. They are most often found in the manufacturing industry as a way to automate simple tasks, such as the transport of materials within a factory.

AGVs have been in use since the 1960s, as the manufacturing industry became more competitive, material handling had to keep pace and AGVs were an effective way of doing this (Yan *et al.*, 2010). In 1973 Volvo in Sweden replaced their conveyor belt assembly with an army of 280 individual AGVs, which was a huge investment at the time (Frog AGV Systems, 2011).

A large amount of research is currently being conducted on the development of other types of AGVs in the form of unmanned aerial vehicles (UAVs) as well as autonomous underwater vehicles (AUVs) (IEEE, 2012). Previously these were remote controlled, but recently research has shifted to autonomy.

A review of the literature on the use of AGCs in industry shows that most of the information is provided by companies that are manufacturing or making use of AGVs themselves. The majority of current research into AGVs used in industry is focused on finding new methods for navigation, mobilisation and odometry. These projects generally make use of expensive equipment for navigation and calculation making it difficult to apply to a project such as this. Examples of these include cameras and accelerometers used by Tkocz and Janschek (2014) for localisation and actuators used by Gomez-Bravo *et al.* (2014) in their hybrid hexapod. While the importance of these technologies and research for future development of AGVs is noted, they were not applicable to this project.

The biggest industry from a financial perspective is still the automation field, and as technology develops more uses are being found for AGVs. This is mainly due to the fact that AGVs have the ability to speed up processes reliably and safely, while saving money, most notably in large-scale production facilities (Pal *et al.*, 2011).

A major factor to be taken into account when designing AGVs is the level of reliability required. As with other robot apparatus they are frequently used for long continuous periods of time. As such reliability is a key factor. Downtime has a direct effect on production: the more often the machinery is offline, the more money is lost.

2.2 Locomotion

Manipulation and locomotion are the two aspects of movement for a robot. A robotic arm is an example of manipulation: the base of the robot is fixed, and the arm moves around it, relative to a fixed point. The opposite of this is locomotion, where the base moves. Locomotion is the focus of this project.

The most common way for robots and AGVs to move around is on wheels. Recently there has been some development in other areas, for example Boston Dynamic's Big Dog (Figure 2.1) and Plustech's Plusjack Lusto (2011) robot. Both employ a leg structure for movement. These systems, although impressive and capable, are extremely costly because of the amount of processing power and actuators required, and usually only benefits from use in certain environments. This form of actuation has found strong applications in rough-terrain where conventional wheeled vehicles with low centres of gravity are unable to navigate many obstacles.

Continuous track systems, such as on a tank, are often used for outdoor vehicles which have to traverse rough terrain. In the manufacturing industry, where the environment is relatively flat, wheel-based motion is the primary method of drive. There is also a large variation in possible wheel configurations that can be evaluated. For the purposes of this project, only wheel-based forms of locomotion will be studied.

Different designs make use of different numbers of wheels, as well as different layouts. From a stability perspective only two wheels are required. This is evidenced in projects such as the Segway (Figure 2.2),which although not autonomous, achieves stability by

Figure 2.1: Concept of Big Dog AGV (Boston Dynamics, 2009)

Figure 2.2: Segway (Segway, 2012)

driving the two wheels independently in a format known as differential-drive. This device requires constant power to maintain drive on the wheels and remain balanced.

In the automation industry, three- and, more often, four-wheeled AGVs are most common. Three wheels have the advantage of not requiring any form of suspension regardless of the terrain. All three wheels will always touch the ground, which means the AGV has constant traction. On unstable ground, a four-wheeled AGV may require suspension to avoid one of the wheels being lifted off the ground and leaving it stranded. However in the manufacturing environment this is usually not an issue as flat concrete floors are the norm and any deviations caused by obstructions or debris are negligible.

There are various means to provide drive for each setup. Differential-drive is very popular as it provides the ability to turn almost on the spot, allowing for greater manoeuvrability. Differential-drive makes use of two independently driven wheels. By varying the speed of the two wheels individually one is able to both turn and drive an AGV. Other popular options include driving two wheels via a conventional differential, and then steering with the remaining wheel/wheels. These are often found in hobby projects, as people modify standard remote control (RC) cars to achieve autonomy (Siegwart and Nourbakhsh, 2004).

2.3 Navigation

The main advantage of implementing an AGV is to have a device which can move around in an area without the need for supervision or human control. Therefore one of the major focus areas of current research is a means for the AGV to navigate its way around a specific area.

Rao (2004) lists the three main forms of guidance for AGVs as 'Wire Guided', 'Infrared' and 'Laser'. While these are certainly popular methods of navigation, recent developments in the area have resulted in several new technologies as well as variants of the original three.

The majority of the newer developments have been in the direction of wireless guidance (Alavudeen and Venkateshwaran, 2008).

2.3.1 Line Following

Line following comprises the laying down of physical lines, whether it be a coloured tape or metal wire. Sensors specific to the type of line are used to monitor an AGV's position relative to the line. The AGV is then programmed to drive along the line, while other sensors that monitor for obstructions or positional markings.

Line-following methods remove much of the difficulty associated with AGV development. Although the AGV will not have information relating to its position along a track, it will not be lost, as it simply has to follow the line. This situation is easy to design, whereas incorporating other navigation elements can increase both the cost and complexity of an AGV system. Bishop (2007) also argues that it is one of the most reliable methods to guide a robot from one place to another.

Wire Guidance

Making use of a wire was the first type of guidance used with AGVs, and remained the dominant method in use until the 1980s when other methods began to take preference. A controller would generate a frequency in the wire which the AGV was able to detect and follow. Antennae mounted on the AGV would measure the amplitude of the signal and control its direction as the amplitude varied. The controller was able to turn different sections of the track on and off, allowing it to navigate the AGV down specific paths or get it to stop when desired.

Although wires were initially mounted above AGVs, later designs entailed embedding a wire path in the floor of the building. This process required a large initial cost and meant that businesses were loath to reroute the system at a later time. Corners also became problematic as the wire had to be laid out in a curve which is difficult to achieve when hollowing out the floor.

In certain installations several wires were laid in the floor to achieve different routes, and included communication protocols. These were known to interfere with each other. Rebar in the ground was also known to cause interference leading to occasional control issues with the AGVs (Frog AGV Systems, 2011).

Vision

Vision control entails the use of one or more video cameras, quite often webcams, to follow a coloured line. The video feed is fed to a controller which applies filters to determine the line the AGV must follow. This data is used to control the motors driving the AGV.

There are several software packages which enable this type of line following. Matlab has several packages such as the Computer Vision System Toolbox, while RoboRealm is a software program dedicated to the development of robots guided by vision-based systems. There is also the Open Source Computer Vision Library (OpenCV) which can be integrated into most major programming languages. The package allows for the digital processing of video feeds.

The use of infrared (IR) sensors can also be seen as a form of vision. By transmitting IR light and using a photodiode as a sensor, the response can be used to locate a strip of tape. The system makes use of a contrast between the floor and a tape that is laid down. The two surfaces will reflect the IR light to varying degrees. The intensity of the reflected light can be measured and a system can thus detect which sensor is currently located on the line. Frequently the floor is a cement floor, so coloured or highly reflective tapes can be used to give a high contrast between the two surfaces. IR sensors can become unstable when exposed to sunshine, due to the large amounts of IR light the sun emits. However in an indoor manufacturing environment, the risk of interference is far lower.

Most of these vision-based systems require the tape to be clean. In the long term this can lead to issues with navigation unless extreme care is taken to maintain the tape (Beccari *et al.*, 1997).

Magnetic Strip

Similar in principle to a vision system, this method uses magnetic strips that are laid down on the floor of a plant to act as guidelines. Sensors capable of detecting the magnetic strips (often some form of induction sensor) monitor the position of the AGV relative to the line. This data is then processed to calculate the AGC's position relative to the magnetic strip and, by continuous monitoring, the drive of the AGC alters its direction to maintain a specified sensor reading. Xing *et al.* (2012) made use of such a system in their material handling AGV.

2.3.2 Dead Reckoning

Dead reckoning refers to the monitoring of proprioceptive sensors to keep track of the robot itself. These sensors monitor the speed at which the wheels turn or how much current is drawn. By knowing the start position and monitoring the movement of the robot it is possible to calculate its position at a later stage by the use of geometry (under ideal conditions).

Unfortunately several factors result in discrepancies between calculated and actual positions. Most often this is because the interaction of the motors with the environment is not ideal. Any number of interferences can occur, causing irregularities with the calculations. For example, the robot's wheel may become caught on a rock; the wheel may continue to turn, while not effecting any forward movement. This can result in calculations based on ideal movement to become inaccurate and the robot to become disorientated (Rosandich *et al.*, 2002).

One way to counter this is to place landmarks at set locations. While moving around, the robot will have the means to identify these landmarks, and on correct identification will be able to place itself relative to the predetermined landmark. Thus even if it gets slightly off track, it is able to reset itself to its true position and continue for another short period using only dead reckoning.

Basic solutions may reset their positions once every few seconds, but other solutions (such as seen in Section 2.3.5) maintain an almost continuous connection to landmarks and thus only make use of dead-reckoning calculations to determine what movements need to be made.

In the early stages of development line-following principles were used in collaboration with dead reckoning. For most of the time the AGV maintained its wire-guided navigation, but when required to turn, dead reckoning would take over temporarily until it found a line again. In this way the need to cut curved grooves for wire placement was removed, and costs were lowered.

2.3.3 Inertial Navigation

Similar in theory to dead reckoning, is an alternative known as inertial navigation. Instead of keeping track of the speed at which the wheels are moving and thus calculating distance travelled; inertial navigation makes use of an accelerometer to monitor the acceleration of an object in space. By following the acceleration of the object in different directions one is able to calculate the speed and position of a vehicle at a certain time. This requires that the initial speed and orientation are known. Specific formulae are then applied to determine the expected speed of the object, and subsequently its displacement.

The biggest problems with this are the amount of processing required, errors that arise with the non-exact values determined from the sensors, and the inherent error in the acceleration readings.

2.3.4 Magnetic Floor

Although not often seen, Frog AGV Systems has formed a business creating an x-y coordinate map by embedding magnets in the floor of a plant, and using these as references for AGVs travelling in a dead-reckoning manner. Frog AGV systems specialise in this form of navigation and have developed their own controllers and software so that anyone can

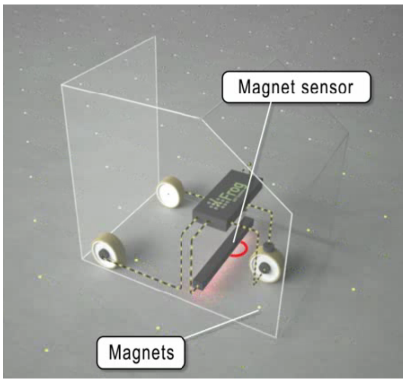


Figure 2.3: Magnet-Sensor Layout for FrogBoxL2 (Frog AGV Systems, 2011)

implement this form of navigation in their own AGVs. This kind of setup can be seen in Figure 2.3.

Frog AGV also sell an array of ready-to-use AGVs which all make use of their proprietary products. The advantage of a system like this is that a lot of the processing work is done by the equipment. By purchasing a FrogBox L2 (their main controller) one can install this system in any factory environment.

The system works by having a map laid out in a grid format. The AGV travels by itself with an indication of the direction and speed at which it is travelling. Each time it passes over a magnet, it can place itself on the map relative to these magnets; in this way it is able to confirm its position every few meters, depending on the specific layout.

A similar system can be developed independently. The selection of sensors would be the most crucial aspect to ensure precise positioning of the magnets in the floor. It would also be necessary to have multiple sensors on each AGV to ensure the correct detection of the magnets. This system does allow for greater flexibility, as one is not restricted to a single line or track and by interfacing with software, one can reroute AGVs with ease (Frog AGV Systems, 2011).

A drawback to the system is the initial installation procedure. Depending on the scale of the installation, it would be necessary to drill hundreds of holes into the floor to place the magnets. Although this would not negatively impact the surface or mobility, it is costly.

2.3.5 Laser (GPS)

A standard Global Positioning System (GPS) works by calculating the difference in time between signals it receives from satellites. The satellites are all in known positions in space running atomic clocks all set to the same time. The GPS device receives signals from several satellites. Each signal includes the time the signal was sent and the position of the that satellite. By using the difference in time between receiving multiple signals (at least four are required), and knowing the position of the satellites in space, one is able to triangulate the GPS receiver's position on Earth, this is because the signals travel at the speed of light.

General GPS receivers have an accuracy of 10 - 20 m. There are methods to improve accuracy to less than 1 m (National Air and Space Museum, 2011), but within certain applications even this is not suitable. One major drawback of GPS for positioning in the manufacturing industry is that GPS signals require line of sight between the satellite and receiver, which makes them unusable in indoor manufacturing environments.

Several methods have been developed to overcome this problem. One of the more successful systems (developed at the Episcopal Convict of Luxembourg (Convict.lu, 2009)) makes use of a combination of IR and ultra-sonic systems. Beacons located around the area at set locations contain an IR diode and ultra-sonic emitter. AGVs roving the navigation area are equipped with IR and ultra-sonic sensors. Every second the beacons transmit a burst of IR light, followed by ultra-sonic waves. The light covers the distance almost instantaneously, but the ultra-sonic wave takes longer. By measuring the time it takes for the ultra-sonic wave to arrive after the IR light, the distance from a beacon can be determined, with claimed accuracies of less than 1 cm.

By making use of several beacons which send different codes, one can determine the position of a robot. Figure 2.4 demonstrates this triangulation method.

2.3.6 Conclusion

Table 2.1 shows that although various navigation concepts exist, many with high degrees of accuracy, along with accuracy comes a high cost factor. If we consider the importance of accuracy in this application it can be concluded that a cheaper system which is 'accurate enough' would be more advantageous to the project than one which is very accurate, but also expensive.

Therefore the researcher decided to adopt a line-following method for this application, as it lends itself to a fixed path which will be navigated repeatedly. The reliability obtainable

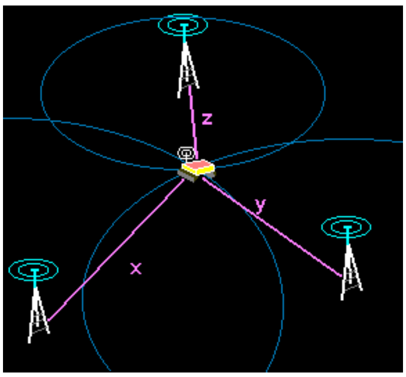


Figure 2.4: Position Determination by Triangulation from Beacons (Convict.lu, 2009)

Table 2.1: Comparison of General Navigation Choices

	Cost	Complexity	Accuracy	**Total**
Laser	1	1	5	**7**
Magnetic Floor	1	1	5	**7**
Line Following	4	4	4	**12**
Inertial/Reckoning	5	5	2	**12**

with line-following methods is also well suited to this application.

As such, a form of line following will be investigated for navigation going forward.

2.4 Sensors

For the purposes of this project only two forms of sensors are required: sensors that will

- be used in the line following process.
- aid the AGC in avoiding contact with obstacles

2.4.1 Navigation Sensors

Line following can take several forms, most notably: a linked path (for example a train track); a camera or other sensor that measures waves in the light spectrum; or some form of magnetic field sensor. Linked path setups are inherently costly, making them unsuitable for these purposes. For both magnetic and visual guidance, both sophisticated sensors capable of high resolution and simple binary sensors are available.

When comparing the sensors, both the high- and low-end sensors compete on both a cost and resolution basis. Therefore, to select one, one needs to consider additional factors, the main one being reliability. Both types of sensors are liable to interference, but from different sources.

Visual sensors work by using the contrast between a line and its surroundings, for example a light line on a dark surface. However, should the line itself also become dark (for example from dirt build-up), the ability of the sensors to differentiate correctly decreases.

Likewise a magnetic sensor differentiates between a substance in which a current can be induced, and one which cannot; for example, a metallic strip on concrete. The sensors however can't differentiate between different metal types, so the entire route one plans must be free of possible interferences. Any metal items, be it scrap metal, equipment or loose nuts and bolts, must be removed from the route.

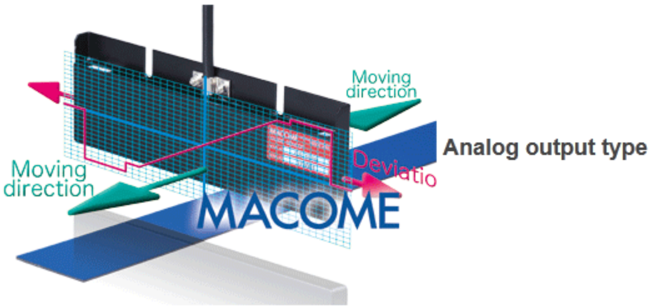


Figure 2.5: AGV Magnetic Guidance Sensor from Macome (Macome, 2011)

Magnetic Guidance AGV Sensor

Several manufacturers sell products specifically designed for use in AGVs and magnetic line following applications. One such company is Macome. One of Macome's products is illustrated in Figure 2.5. Two variants are available: one gives an analogue output varying with the position of the magnetic tape relative to the sensor, and the other a parallel output where high and low readings relate to positions on the sensor whether within a magnetic field or not.

Quotes received from Macome (Macome, 2012) indicated a cost of R 8 380 per unit, reducing to R 7 330 for orders of twenty or more units. Such a cost would have a major effect on the budget for a low-cost AGC.

Induction and IR Sensors

The magnetic guidance sensor referred to above is effectively an array of induction sensors. Although the sensor mentioned gives a reasonably high resolution regarding the position of the AGV relative to the magnetic tape, similar information should be obtainable by using several induction sensors.

By positioning two sensors a few centimetres off centre of the AGV one is capable of obtaining sufficient data to navigate. The sensors would sit an equal distance from the centre, on either edge of the magnetic tape. When correctly centred and driving in a straight line, both sensors would return active values. If the magnetic tape turns left, or if the AGV is not going perfectly straight and veers slightly to the right, the reading from the right sensor would deactivate and that from the left sensor would activate. The control mechanism would then be instructed to turn to the left.

Many hobby roboticists make use of this kind of system but with IR sensors instead of magnetic sensors. *The Robot Builder's Handbook* (Bishop, 2007) makes use of this technique as illustrated in Figure 2.6. In the two left examples only one sensor receives feedback which means the robot must turn in the opposite direction. The third example shows the robot moving in a straight line, with the sensors located just either side of the

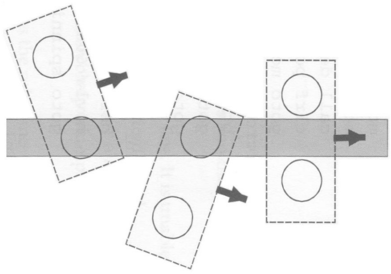


Figure 2.6: Infrared Sensor Setup for Line Following (Bishop, 2007)

line.

While IR sensors can be used in the same manner, they differ from induction sensors in one or two ways. IR sensors can be used with a cheaper material for the line. Something as simple as insulation tape can be used, although this is likely to get damaged quickly. More robust materials are available, including reflective tape similar to that found on road going trucks and trailers. Induction sensors require a metal tape, preferably something non-corrosive such as stainless steel, this is more costly, but also more durable.

The areas where the AGC was to be used is comprised of concrete sections separated by expansion gaps with steel inserts. When travelling over these surfaces induction sensors would lose the track, but this could be dealt with in the software. IR sensors would also be susceptible to similar interference as the surface changes along the route. Induction sensors are marginally more expensive than IR sensors (10-20%), increasing the cost of the project by at most R 500.

Conclusion

Table 2.2 sets forth the main options to choose from with reference to a method of navigation in comparison to the main three factors taken into consideration for determining the optimal option. Induction refers to the use of individual induction proxies in an array to sense position. Magnetic refers to a specifically designed magnetic line following sensor. IR implies the use of IR proxies in the same manner as the induction proxies. Visual refers to a camera setup to process line position.

As far as the track was concerned, the magnetic and induction options would require the least maintenance as they would be less affected by dirt build-up and obstructions in comparison to IR or visual systems. From cost perspective, the induction and IR proxies are significantly cheaper than a magnetic line following sensor or camera setup. However while being more expensive, they provide much higher resolution feedback than the proxies.

Looking purely at cost, it would not be possible to stay within budget while using either the magnetic line following sensor or the camera setup. With the Induction and IR

Table 2.2: Comparison of Specific Navigation Choices

	Cost	Maintenance	Effectivness	**Total**
Induction	5	4	3	**12**
Magnetic	1	4	5	**10**
IR	5	2	3	**10**
Visual	1	2	5	**8**

proxies having a similar cost it was determined that the induction sensor offered the best compromise.

2.4.2 Proximity Sensors

Bumper

Most often a bumper comprises of an arm which, when pressed against another object, is pushed inwards activating a microswitch. It is a simple and effective system, although it does require actual physical contact to activate. In certain situations this not ideal, particularly when a robot is moving at speed. By the time a bumper switch is activated, it is too late to slow down, possibly resulting in damage to the AGV.

Despite this drawback, research into other solutions shows that it is standard procedure with AGVs to install a bumper, even if other proximity sensors are in use. This is to protect the AGV in case of impact, minimising the force and damage experienced.

One of the following solutions can be used to detect objects close at hand, before interaction occurs.

Ultrasonic

Ultrasonic sensors work by transmitting ultrasonic waves and waiting for the reflection against an object to return to the sensor. By measuring the time it takes for the reflected wave to return and knowing the speed of sound, one can calculate the distance to the object.

Different sensors are set up for different ranges, although they generally have a dead zone close to them in which objects are not registered. This is because of the design of the sensors: for a few milliseconds during and after transmission of waves, the receiver is turned off, thus prohibiting the sensor picking up waves that return in too short a time.

Under ideal circumstances commercial sensors have an accuracy varying between 98 and 99.1% (Siegwart and Nourbakhsh, 2004), with the object perpendicular to the direction of wave propagation. If the angle is too obtuse, it may cause the waves to be reflected away from the sensors, thus losing the signal. Furthermore certain materials may absorb the waves, also resulting in the object going undetected. A material of particular concern is cloth, as this will be the material most likely worn by operators working with the AGC.

Another problem relating to ultrasonic sensors is the frequency at which measurements are taken. If the maximum distance that the sensors measures is 4 m, it will take close to 25 ms to receive the signal. This limits the sensors to checking 40 times a second. If one has 15 sensors (assuming a small viewing angle) set up on the robot, it means a full cycle can only take place three times a second. At low speeds this may not be a problem but this is simply not fast enough to achieve adequate mapping when AGVs requiring full environmental scans at high speed are being used.

Infra-Red

IR systems work on the same principle as ultrasonic sensors. A combination emitter/receiver is placed into one unit to determine the distance to nearby objects. A beam of light is emitted and the time it takes to hit an object and return to the sensor is measured. The distance to an object can be calculated from the speed of light.

Generally these calculations are performed internally by a controller in the sensor and one need only read a value from the sensors to determine a live reading of the distance. The far higher speed of light compared to speed of sound, means that hundreds of readings can be taken every second, making it a more suitable option than ultra-sonic sensors (Benet *et al.*, 2002).

One disadvantage is that IR sensors are susceptible to interference from natural light sources.

Laser Range Finder

A laser range finder works in much the same way as IR sensors. However the focused beam of the laser allows for greater accuracy and faster scanning times. Range finders are often incorporated with a mechanism to rotate a mirror, allowing a single sensor to scan in either one or two dimensions.

One type of laser system operates similarly to the ultra-sonic system, where a beam is shot and the time between the signal leaving and the reflected signal returning is measured. However a more common method also takes into account the change in phase that occurs when waves are reflected, as can be seen in Figure 2.7.

By measuring the phase difference the distance to the object can be calculated.

These devices are often found in AGVs, both for their ability to help map and navigate areas as well as for obstacle avoidance. Many commercial AGVs make use of them to prevent their bumping into objects and people. They are also used extensively in industrial

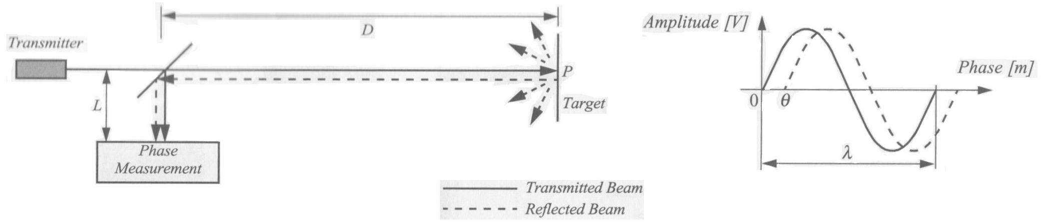


Figure 2.7: Phase Change in Laser Transmission (Siegwart and Nourbakhsh, 2004)

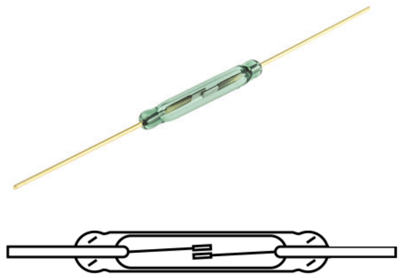


Figure 2.8: Diagram and schematic of a reed switch (RS Components, 2015*a*)

production lines as a safety check to ensure machinery does not operate when someone is too close. Laser range finders provide a higher level of accuracy and are less affected by different surfaces than the IR and ultra-sonic comparable options. Although desirable for use in this project, entry-level laser range finders can cost R 10 00, in comparison to a more affordable R 600 IR sensor.

Magnetic Switches

Reed switches are easy to use: discrete switches toggle when in the presence of a magnetic field. By placing individual magnets on the floor at specific points, an AGV can be triggered to perform certain actions. Reed switches are fairly cheap and come in a wide variety of forms. Magnets are also readily available.

A reed switch is comprised of two separate wires suspended close to each other in a closed environment. When a magnet passes near the sensor, the two wires are brought together, shorting the circuit.

More advanced systems such as radio-frequency identification (RFID) also make use of an effective magnetic field. RFID scanners create a magnetic field, and a current is induced in RFID chips in the presence of the scanner. This powers a small circuit which wirelessly transmits the data in the RFID card to the scanner.

RFID scanners can be placed on an AGV and RFID cards placed at certain locations on the floor. As the AGV passes over the cards, it can individually differentiate the various cards and gain locational awareness, facilitating the commencement of different activities at various locations.

Conclusion

For collision avoidance an IR proxy would be used over an ultrasonic sensor or laser range finder. The use of a laser range finder would put too much strain on the budget to be viable, and sufficient feedback should be obtainable with proxies. Relative to the US sensors, IR sensors should provide better response to obstacles expected in the manufacturing environment. A bumper will also be included should the proxies fail to detect an obstruction in time. The bumper will include a switch to stop the AGC if a collision occurs.

An RFID sensor will be used in tandem with cards placed along the track to allow for feedback of where on the route the AGC is.

2.5 Control

2.5.1 PLCs

Programmable logic controllers (PLCs) have long been used in the automation and manufacturing world for a variety of applications. As far as functionality is concerned PLCs fit somewhere between microcontrollers and computers. The major factor distinguishing PLCs from these others is that PLCs are designed with heavy duty applications in mind. Designs are more rugged and based on a *plug 'n play* structure, where components can be quickly and easily replaced, or integrated into a unit.

Another contributory factor to the popularity of PLCs in the manufacturing industry is the relatively basic programming style in the form of function block diagrams (FBD), also known as ladder programming. This is a way to program PLCs by making use of a flowchart-type interface. It is fairly simple and does not require a conventional background in programming. It is also often easier to fault-find while the program is running through an FBD, as areas light up when activated. PLCs can also be programmed in a more conventional way by making use of structured text (ST) syntax.

2.5.2 Microcontrollers

Microcontrollers are present in almost every electronic application currently in use. They are small, cheap and are generally used in applications where one time programming is appropriate. In general microcontrollers consist of several input/output (I/O) pins (digital and analogue) with settings to allow for certain communication such as via I2C (Inter-Integrated Circuit) or various serial protocols. Their low cost and high variability make them a good choice for many applications.

Microcontrollers can be programmed making use of the assembler programming language but more often separate compilers using a higher-level language are used to simplify the programming (Hamrita and McClendon, 1997). An in-depth understanding of the microcontroller is required as I/O pins have a variety of functions and restrictions, and require setup procedures before they can be used. This is usually considerably simpler when using a PLC.

Unlike a PLC, which can be plugged directly into a power supply and be ready for use, a microcontroller often needs extra circuitry and it is usually necessary to develop a PCB (printed circuit board) for individual applications. These factors increase the cost of development but prices are still generally lower than PLCs.

2.5.3 x86 Computer

Certain designs require a computer running custom or proprietary software to control the robot. For example AGVs which navigate making use of cameras, either line following or for obstacle avoidance, often run software such as RoboRealm or Matlab to do large amounts of video processing. These computers are usually based on the common x86 computer architecture and often run a version of Windows with their specific software loaded (Carnegie *et al.*, 2004).

In such instances, microcontrollers and PLCs generally cannot provide the processing power required for the successful functioning of the AGVs. Furthermore, software is most frequently designed to run on a Windows- or Linux-based operating system (OS), which cannot be run on standard PLCs and microcontrollers.

Single board computers (SBC) can often be found in prototype AGVs. Their small form, relatively high processing power and ability to run conventional software make them easy to use and program. In general computers are more expensive than microcontrollers and PLCs, but several low cost SBCs can be found for less than equivalent PLCs. An example of a popular SBC is Texas Instruments' Beagle Board which includes USB ports, Ethernet, Audio, Video, expansions for UART (universal asynchronous receiver/transmitter), I2C and other I/O ports (Texas Instruments, 2011). Their unit price is just over R 1 500 (RS Components, 2012*b*).

2.5.4 Conclusion

To choose the best option for this application, the controllers were rated on four factors, namely:

- Ease of use: relating to requirements for setting up and programming;
- Reliability: indication of expected reliability / stability of the controller;

- Sensor integration: ease with which IO devices can be connected to the controller; and
- Cost: the cost of the controller itself, as well as relative cost of sensors and other required support electronics

These factors are compared in Table 2.3.

While a microcontroller was the cheapest, costing less than R1 000 to implement, designing a board and the required support electronics to ensure good sensor integration and communication could be time consuming. There was also the issue of reliability. While microcontroller systems can be designed to be stable and able to run for extended periods without issue, this generally requires a large amount of development and time put into testing.

A second option was the use of a SBC. These come as complete units requiring only a suitable power supply, but still require to be set up and get functioning properly. Extra circuitry could be required to ensure voltage levels are correct depending on the sensors selected. While cheaper to buy and set up than an equivalent PLC, a SBC would still cost twice as much as a suitable microcomputer setup.

Ultimately the researcher decided to use a PLC. Although costing four times as much as microcontroller, several benefits made it the most appropriate choice. PLCs are easy to set up: they run as soon as power is provided. They are used in industry and make use of standardised sensors which can simply be plugged in and function instantly. PLCs come with standard connector blocks allowing for easy maintenance and setup.

Maintenance is another benefit of using a PLC. With a standard program run on a microcontroller, very little in the way of debugging can be done should the device malfunction. Debugging information has to be programmed directly into the software and output via a serial connection or display screen. With a PLC, maintenance personnel can plug a computer directly into the PLC and download the code onto the computer. The program can then be monitored as it is running, viewing the response to various inputs and outputs. This makes fault finding easier. ‘Ladder Programming’ language also aids in the problem finding exercise.

It would also advantageous for the staff at GMSA to be able to edit and update the program controlling the AGC, as it was still in the form of a prototype. This was made

Table 2.3: Controller Decision Matrix

	Ease of Use	Reliability	Sensor Integration	Cost	**Total**
PLC	5	5	5	2	**17**
Microcontrller	2	4	3	5	**14**
Computer	3	3	1	3	**10**

far easier with a PLC, as simply connecting to the PLC allowed one to download the code and quickly make changes.

2.6 Drive

2.6.1 DC Motor

DC motors are found in many applications throughout various industries. They are simple to control, with their speed being proportional to the voltage applied, and the torque delivered being proportional to the amount of current delivered. DC motors come in a variety of form factors and sizes, making it easy to find a motor suitable for a specific application. Certain models can also be found with gearboxes which allow for higher torques at lower motor speeds.

2.6.2 Stepper Motor

Stepper motors are a form of DC motor with the inherent design feature that they have the ability to move in steps. The motor is comprised of separate coils, and a toothed, permanent magnet rotor. By alternating the excitement of the coils, a stepper motor can be rotated in set increments, which vary between 0.5°and 45°.

Stepper motors are slightly more complicated to control, requiring the correct generation of signals to different coils to achieve continuous rotation. When driven at slow speeds, and especially with larger step sizes, stepper motors are known to produce a characteristic jerky motion.

One of the main advantages of a stepper motor is its ability to control position; however for driving a wheel at differing speeds this is not a major factor. In addition this positional control comes with an increase in current draw. High-torque stepper motors, as required for this project, are very expensive, with some motors being six times more expensive per motor compared to a DC motor of similar power ratings (RS Components, 2015*b*). Stepper motor controllers also tend to be fairly expensive.

2.6.3 Servomotor

Servomotor is a general term covering a form of motor that includes some form of variable control, most often that of position. This is achieved by including an encoder in the product. The motor itself is then able to govern its position or, less commonly, angular velocity based on the input and feedback from the encoder. Depending on the desired application of the servomotor, there are various types for the different industries (Bakshi and Bakshi, 2007). These can include various styles of DC servomotors, synchronous type AC servomotors and induction type AC servomotors (Suh *et al.*, 2008).

Although widely used, a slight premium is paid for the internal positional control inherent in a servomotor. For the application in an AGC where only a driving motor is to be considered, the extra benefit is not particularly gainful, and as such a servomotor is unlikely to be the best choice for the application. The servo motors considered were low-torque, high-speed motors. Those of similar power ratings to DC motors were several times more expensive and additional gearing would be required to make them usable in the project.

2.6.4 AC Motors

AC motors are common in the industrial environment. They work directly off mains voltage lines and can be designed to be used at set speeds, without requiring any type of converters. To help with line balancing and provide extra power, the majority of the motors used in the industry are also three-phase motors.

The term low-voltage, when applied to AC motors, refers to motors running at the 220 VAC level (Siemens, 2012*a*). Working with these motors is mostly straightforward when running in an industrial setup off a mains line. However, the difficulty arises when wanting to design a mobile unit that does not have direct access to mains lines and would need to source power elsewhere. When running off batteries (typically in the 12 - 48 V DC range) one would require an inverter, and if three-phase power were desired, it would greatly complicate matters.

However, there are other means of supplying power to a mobile unit (see Section 2.7), which would make AC power a reasonable solution. Nevertheless, in most instances where a device does not have a direct connection to a mains line, some form of DC motor, such as those discussed, is a more suitable option.

2.6.5 Motor Control

Although technically possible to control some motors directly from a microcontroller or PLC with the use of some custom electronics, the control and ease of use provided by dedicated motor controllers make them the preferred method of control in industry. Motor controllers further provide safety and aid integration with existing platforms.

Various motor controller boards are available to suit any type of motor. Different types of motors require different controllers. When selecting a controller one must ascertain that its voltage and current ratings specifications fall within the demands of the motor. A further imperative is the method of communication with the controller itself. Certain controllers will accept certain digital communication protocols, whereas others may require an analogue voltage.

Table 2.4: Comparison of Main Motor Factors

	controllability	incorporability	size	cost	**total**
DC Motor	4	4	4	4	**16**
Stepper Motor	4	3	4	3	**14**
Servo motor	5	3	3	3	**14**
AC Motor	4	2	2	3	**11**

2.6.6 Conclusion

For the purposes of this project it was decided to use DC motors to drive the vehicle.

Table 2.4 summarises several of the factors discussed. The table reflects fairly even results for all but the AC motor, which was deemed impractical for a DC powered AGV (refer to Section 3.3). However from a practical perspective, the DC motor is better suited to a continuous drive situation such as this. Stepper- and Servo- motors, while having good controllability, are preferred for a constant-position or -drive application. Coupled with this, the lower cost and ease of incorporating a DC motor into such a system made DC motors the top choice.

2.7 Power

To ensure continuous operation of the AGV, some form of power is required to drive the motors and circuitry. The device cannot merely be plugged in as unimpeded movement of the AGV becomes an issue. The main selection choices are:

- Battery power (the most common);
- Fixed continuous connection (ie. subway/tram systems); and
- Wireless continuous connection.

2.7.1 Batteries

Powering AGCs by battery is the most common method of operation. The main disadvantage is the continuous charging and replacing of batteries required. Although many forms of batteries are available, few are suitable for AGCs. One reason for this is AGCs are known to draw currents in excess of 30 A. Depending on the application, battery capacity can also play a large role in battery selection.

When selecting a battery type many factors must be considered. For this application, the main factors considered were:

- Cost per unit energy;

Table 2.5: Comparison of Main Battery Factors

	Cost	Lifetime	Energy Density
Li-Ion	R4.33 / KWh	1000	High
NiMH	R6 / KWh	1000	High
Lead Acid	R1 / KWh	500	Medium

- Lifetime; and
- Mass/volume per unit energy.

The three main types of rechargeable batteries found in operation are Li-Ion (lithium-ion), NiMH (nickel metal-hydride) and lead-acid (Barnes *et al.*, 2011). Li-Ion is most commonly found in consumer electronics such as cameras and cellphones, and is currently finding wide use amongst hybrid-electric vehicles. NiMH batteries are regularly used in consumer electronics as replacements for standard alkaline batteries. Lead-acid batteries are most widely found in cars and other vehicles as a means to power the vehicle's starter engine. They can also be found in forklifts and as a storage system for solar-electric and other backup battery systems.

Table 2.5 compares these three battery types against the evaluation criteria. From this we can see that while Li-Ion batteries have an extended lifetime and occupy less space for a similar energy storage capability than the other options, they also have the second highest cost per unit energy. Lead-acid batteries on the other hand are considerably cheaper, but occupy more space and are notably heavier. NiMH batteries are more expensive than equivalent Li-ion.

2.7.2 Charging vs Rotating of Batteries

A further consideration when making use of battery power is the management of charging. The two main alternatives in practice are:

Battery rotating

AGCs are designed to operate for a determined number of hours. At the end of this time, or when the battery voltage becomes too low to operate, the AGC is directed to a specific location where the batteries are changed. Depleted batteries are then set to charge until the next switch, allowing for continuous use of the AGC, apart from the ten minutes required to switch the batteries.

Although popular in constant-production facilities, this is fairly expensive as a minimum of one extra set of batteries is required and the switching of batteries can be disruptive.

Installed charging

The AGC is installed with a set of batteries adequately charged for its shift. At the end of the shift it is sent to a central area where it can be plugged in and set to charge. This results in a downtime in production as charging can take several hours and usually is not considered feasible in constant-production facilities.

A variation on this is to locate automatic charging stations at set places around the AGC's track. The AGC is then docked at these points while waiting for the next process to start. The ability to do this is dependent on the amount of AGCs in use and also the specific requirements of the AGC.

2.7.3 Constant Power

The alternative to batteries is a system where the AGV can be connected to a continuous power supply. For certain larger AGVs, battery power is simply not feasible. The number of batteries required, and the extent to which they require recharging becomes excessive in light of the larger AGV's power requirements. Even in smaller AGVs, the convenience of not having to charge batteries should not be overlooked. There are two approaches to consider here.

Induction Floor

This system makes use of induction in long coils to power the AGV, by transferring the power to suitable coils within the AGV. By passing an oscillating current through a coil a magnetic field is created. When a suitable coil adjacent to this, such as on the AGV, passes through the magnetic field a current will be induced in it. Although new technologies are being developed, induction can typically only be used efficiently with a small air gap (allowing for some antenna misalignment), less than 1 cm (Imura and Hori, 2011).

In order to use this application for powering AGVs, a large set of coils is installed in the floor along the length of the AGV's track. This form of induction is the same principle that is applied in electrical transformers and new wireless charging stations for cellphones and toothbrushes.

One shortfall of this method is that it may lead to a low efficiency of power transfer. The level of efficiency and the amount of current that can be transferred is dependent on as small a gap as possible between the ground and the AGC. However the major shortfall is the installation of the system, which requires cutting routes into the floor.

Powered Guide Rails

Another solution to providing continuous power is to have a system similar to the trains in South Africa, or the subways in the United States of America (USA). In South Africa power is provided to electrically driven trains by overhanging wires which stretch the length of the train tracks. This power is out of the way and the train maintains a continuous connection with the overhanging wires. In the United States, subway trains have a third rail which is powered (Rabban *et al.*, 1997). An extra wheel on the train maintains contact with this rail, providing power to the train.

Although this kind of system can be used effectively within the context, high installation costs and difficulty with the rerouting of tracks or overhead wires can lead to problems. While the use of this kind of system creates a danger because of open conductors, reasonable steps can be taken to minimise this risk.

2.7.4 Conclusion

While GMSA put forward a suggestion for the use of the AGC, it was discussed that this should be able to be implemented into their current production line with flexibility in mind. In this situation the benefits of a battery powered solution put it a head of a design which allows for constant power. Mainly the lack of initial time and monetary investment required in comparison to a constant power design. The main disadvantage of a battery solution being the need to recharge the batteries is a situation which is already well-managed in the manufacturing environment and should be easily integrated.

2.8 Legal Requirements

Because the AGC would be used in a manufacturing environment, certain laws and regulations must be taken into account for the safety of workers. In the USA, AGCs and similar vehicles are governed by the American National Standards Institute (ANSI) and American Society of Mechanical Engineers (ASME) B56.5 standards document entitled *Safety Standard for Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles* (ITSDF, 2005). The standard was first instituted in 1978, and sets out guidelines for the design and use of vehicles with automated functions. This includes regulations for factors such as visibility and cut-off switches as well as the interaction of the vehicles with operators.

The standard is not legally binding, and serves only as a guideline, but it is expected to be implemented on a voluntary basis by all users of guided industrial vehicles.

This standard has not been incorporated into the South African National Standards document, *Industrial Trucks - Additional Requirements for Automated Functions on Trucks* (SANS 24134:2007), which is applicable to vehicles with automated steering (SABS, 2007). This document, like the American equivalent, is focused mainly on the safety aspects of having automated vehicles in a working environment. The SANS document is also intended as a guideline, and no legislation is applicable.

However, it is advisable to keep the contents of both documents in mind when designing such vehicles.

While almost the entire ANSI ASME B56.6 document is applicable, several sections are specifically important to ensure a safe installation. These include sections on the following subjects:

- The marking of routes and areas where the AGV would be active (§4.7);
- The training of users in the correct operation and understanding of function of the AGV (§6.1 & §6.3); and
- Design and construction standards relating to guidance, travel performance, emergency responses, documentation and other functions (§8)

In the same manner SANS 24134 also includes several sections of interest, including:

- A list of potential hazards with guidance on how to minimise risk (§4);
- Safety requirements for automated travel and emergency switch offs (§5.4 & §5.6.2); and
- List of suggested training topics (§7.2)

2.9 Industrial Control Systems

The larger a factory or manufacturing environment, the more complex it becomes to manage one's inventory and processes. Over the years several types of systems have been developed with management and observation abilities. Supervisory control and data acquisition (SCADA) is an example of such an implementation. SCADA does not refer to a specific technology or product, but to any system used to monitor and control a large environment (Berry, 2011).

SCADA systems provide real-time monitoring and control which help increase efficiency. In certain implementations it can be used merely to minimise the frequency of human checks on a system; in others, full systems can be controlled without the need for human interaction. Feedback is provided which can be monitored by an operator to ensure that the system is running correctly. SCADA systems provide instant access to information that can cover a large area. Response time to critical issues is minimised and logging enables long-term analysis and identification of problem areas.

Many companies specialise in proprietary hardware and software for SCADA interfaces, but as there are no specifications for qualifying SCADA, there is a huge variety of types of hardware and software available that can be used to develop a SCADA interface. All that is required for a SCADA setup is a:

- A master unit where data is collected and made available;
- A remote terminal to gather data;
- A communication medium to transfer the data.

In this project a SCADA system would mainly be used to monitor the AGCs to ensure they are all running correctly and provide an early warning to operators should problems occur. It would also provide statistics on the frequency of operation of the AGC system.

2.9.1 Remote Terminal Units

The easiest way to implement a remote terminal unit (RTU) is to make use of the control system already implemented in the AGC, which has to deal with controlling the AGC and monitoring all its inputs. By incorporating a communication protocol in the system, it can be directly included in a SCADA system. The AGC would also have to interface with this device to ensure appropriate communication throughout the system.

2.9.2 Master Terminal Units

Master terminal units (MTUs) are required to process all the data from the RTUs and display it in a format that is easily manageable.

As with the RTUs, commercial products are available which can manage the system, but an easier option would be to make use of an ordinary computer. A computer has a far wider range of products and services, and is easily interfaced with existing networks and databases.

2.9.3 Communication

To link the RTUs with the MTU a specific communications protocol will be required. Using a protocol ensures data transferred is easily interfaced with other systems and is reliable. For the AGC application, a wireless protocol will be applied so that no fixed-wire connection is necessary.

A standard Wi-Fi protocol could be interfaced for easy implementation into an existing infrastructure, or other options such as the Zigbee set of low cost, low power wireless devices are available.

2.10 GMSA Electronic Standards

GMSA contracts out a large amount of design work to engineering design firms. Different firms will receive projects from different divisions within GMSA. To ensure that all products conform to some standard, which helps with maintenance and integration of products, GMSA have a database of standards documents which all equipment must adhere to. Details of the standards range from what different colours represent, to specifics regarding the sourcing of spare parts.

Although this project was undertaken in a similar fashion to a contracted project, not all guidelines were followed, as specific aspects of the standards documents were not applicable. The main reason for this was that this project is more focused on prototyping a low cost solution. Changes can be made at a later stage to overcome any shortcomings.

Nevertheless, the researcher was cognisant of the main regulations applicable to this project so that changes that may be needed could be budgeted for.

Table 2.6 lists the most important standards taken into consideration in the design of the project. This standards document (DMC Facilities Planning, 2000) lists several other standards which apply to motor control, but due to the wording it is assumed these apply only to AC and three-phase motors, used in a static position; they were therefore not included.

2.11 GM Thailand Design

In 2011 GMSA requested that GM Thailand work on a design for an AGC. GMSA received a 20-page document containing several photos, descriptions and rough schematics of a prototype design. An assembly image of the prototype can be seen in Figure 2.9.

The information from GM Thailand is difficult to follow: for instance, the presentation sometimes makes reference to general components, but no specifics are given to manufacturers or model numbers. Furthermore virtually no reference is made to any design procedures that were followed, such as how power requirements were calculated.

At times the presentation references different components and methods. Near the beginning of the presentation a three-wheeled AGC is shown, with a steering column controlled by a servo motor. A motor is attached to each of the other two wheels, apparently on the steering arm to allow for turning as the steering angle changes. A later slide indicates the use of a standard differential-drive method.

Certain images indicate a three wheeled AGC, while others represent a four wheeled one. Photos of components used indicate a 250 W motor, whereas the cost breakdown indicates that 500 W - 1000 W motors are used. Discrepancies like this make it difficult to define

Table 2.6: List of GMSA Standards (DMC Facilities Planning, 2000)

Sec.	Title	Requirement
§1.3	Spare Parts	List of spare parts included with tender
§1.5	Drawings, Symbols etc	Submit outline drawings and pamphlets...
§1.8	Operating, Maintenance and Servicing Procedures	Contractor shall instruct Employer's appointed representative in routine operating, maintenance and servicing procedures
§11.9	Pilot Lights	Red is power on, green is run, blue is in forward motion, amber is in reverse motion, white flash is abnormal
§11.13	Push Buttons	IEC style 947, 22.5mm and flush. Emergency stop will be mushroom push to stop and lock, with key release. Start is green, stop is red, general is black. Start will be guarded, stop will be unguarded.
§11.15	Limits and Sensors	Shall conform to IEC standards.
§11.16	Photo Cells and Proximity Switches	temps, voltages, humidity
§11.17	PLCs	Control voltage, battery backups required, status indicators that are necessary
§11.18	Electronic Drive Systems	States that AC motors must be used
§15.1	Control Circuit Voltage	24V
§15.2	Circuit Design General	Fail safes etc
§15.5	Automatic and Manual Mode	Circuit designed to return to neutral on power interruption...
§15.7	Stop Circuitry	Rules on emergency stop etc
§15.39	Programming Devices	systems be designed such that one com port is always available
§16.1	Conductor Identification	24VDC control connections are grey, PLC IOs are numbered cores
§17.1	General Diagnostics	Pilot lights will be included for the following, power, motors, mode, fault,

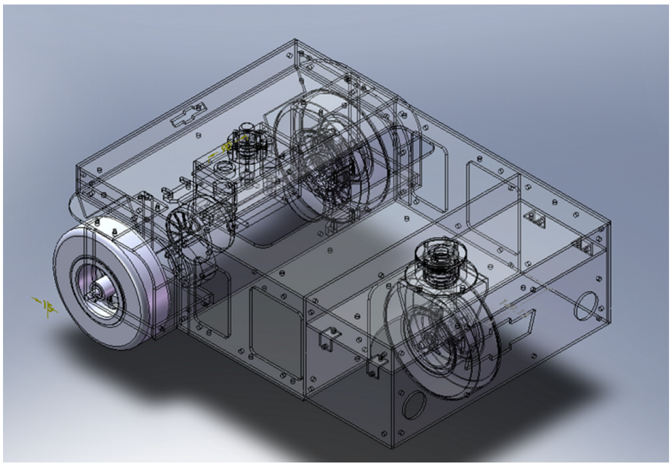


Figure 2.9: Assembly Drawing of GM Thailand's Prototype (Santirakyothin, 2011)

what was intended, and what was actually tested.

The presentation provides a very simple list of user requirements. However no mention is made of the AGCs capabilities with regard to weights it can transport or speeds it can achieve, nor is any indication given as to how components were selected.

Table 2.7: Cost Breakdown of GM Thailand's Prototype (Santirakyothin, 2011) Rand values calculated at exchange rate of THB 1 = ZAR 3.95

Part	**Price (R)**
Batteries	3 800
Motors	6 330
Motor Controller	5 070
Induction Sensors	3 800
PLC	8 870
Wheels	1 900
Tow Pin Assembly	3 800
Body (laser cut)	2 530
Magnetic Contractors	510
Steering Shaft	1 260
Drive Controller	3 040
Magnetic Tape	1 140

A cost breakdown given by GM Thailand can be seen in Table 2.7

Ignoring the magnetic tape (which is a once-off cost and not dependent on the number of AGCs), the total cost for one of GM Thailand's AGCs amounted to R 40 910. If components for twenty AGCs were ordered the cost might be lowered, and the prices quoted are for components sourced within Thailand. The majority of these components are manufactured in East Asia, and the cost in South Africa would be higher.

Looking at Table 2.7 it can be seen that the major costs lie with the motors and controllers, the biggest cost being the PLC unit. Other large costs relate to the batteries, sensors and tow pin assembly. Motors and motor controllers are expensive, and it would be difficult to lower the cost of the design without compromising quality. The tow pin assembly illustrated in the design is a complex one, with a powerful motor that drives a worm gear, forcing a shaft up and down. The researcher considered this over-designed for the purposes of towing, especially at a cost of close to R 4 000.

The tow pin has to be capable of handling fairly high forces, but this does not apply to the actuating mechanism, as the direction of actuation is perpendicular to the towing force. Capable linear actuators can be purchased for less than R 500 (RS Components, 2012*e*) which comprise a closed unit with a shaft that can extend and retract. These units are smaller, cheaper and use less power than the one in the GM Thailand design.

The next component to be considered is the PLC. PLCs have long been used in the manufacturing industry. They are built for tough environments where abuse is more common. They are put into use in a modular fashion to facilitate modifications and repairs. They are often programmed using FBDs as this is a straightforward way to symbolise the working of a system, and aids in fault finding. However they are expensive. On average PLCs sell for over R 4 000 but this frequently excludes the necessary port expanders.

Microcontrollers on the other hand, which can replace a PLC, sell for less than R50 per unit. Extra components and circuitry are required, notably relays, but costs could still be kept to less than R 600 per effective unit.

One of the cost-saving measures that is noticeable in the GM Thailand design is the use of three induction sensors in place of more commonly found magnetic guide tape sensors. The listed cost of these sensors is R3 800, compared to R8 380 for magnetic guide tape sensors (as seen in Section 2.3.1).

2.11.1 Conclusion

While the GM Thailand design appears to be a working prototype, several of the selected components seem over-designed and their resultant expense unwarranted. The exact performance of the prototype is unknown, however it appears that it is capable and several aspects of the design, such as the small size and component selection, should be considered for this project.

Chapter 3

Research and Design

3.1 GMSA Specifications

In consultation with GMSA a set of requirements for this project was compiled. GMSA required an AGC for general purposes. Although they had a current specific application in mind, they also desired that the AGCs could be used elsewhere in the factory with minimal modification.

GMSAs primary objective was for the AGC to be cost-effective (less than R 35 000 per AGC), by minimising costs and complexity, while simultaneously maximising the usability and reliability of the AGCs.

The following specifications informed the project: the cart

- Must be able to run the entire shift on one charge and will be charged between shifts (GMSA currently operate one shift per day of 8.5 hours).
- Does not require automated charging, but can be plugged in by a worker.
- Must travel on a closed loop of between 60 m and 100 m.
- Will be required to do up to 120 loops in a shift.
- Must be able to autonomously navigate a laid out route.
- Should only require human input when having stopped at a marker.
- Should travel at a speed equivalent to a walking pace (1.5 m$\cdot$s^{-1}).
- Must be capable of towing loads of up to 200 kg (absolute maximum) in the form of a wheeled trolley.
- Must not be higher than 0.5 m. This includes the wheels and battery.
- Should not be wider than 400 mm.

- Should have the control interface situated at the front for easy access.
- Should be able to stop at recognised checkpoints and await further instructions.
- Should allow the manual hitching of a trolley.

Safety was also a large concern, both for personnel on the plant and protecting the AGC from damage:

- The AGC should be capable of stopping should it sense an obstruction, and stop and await user intervention should it collide with an obstruction.

3.1.1 Alterations to requirements

While the majority of the design work done focused on this set of design requirements, certain changes to the scope of the project did occur after the project started; these are discussed in the relevant sections below.

3.2 Motor Requirements

One of the critical components of the design is the drive train. Motors need to be capable of overcoming two main forces: the first is the force required for accelerating the AGC and trolley to the desired speed, and the second is the combined resistance forces of constant speed and turning.

3.2.1 Combined Resistance Forces

The Resistance the AGC experiences is comprised of rolling resistance and a combination of resistances found in bearings, gears and motors. Rolling resistance is the product of several factors, mainly deformation between wheel and ground ((Reif and Dietsche, 2011)). For this second set of forces it is difficult to determine a set value; thus an average efficiency rating is used, drawing on previous examples. For rolling resistance there is some theory on which to base a calculation.

The coefficient of friction (μ) for rolling resistance for a car tyre on concrete is listed as between 0.015 and 0.021 (Gillespie, 1992). A formula for rolling resistance is given by

$$\mu_r = \frac{R_x}{W} = C \cdot \frac{W}{D} \cdot \sqrt{\frac{h_t}{w}} \tag{3.1}$$

Where R_x = rolling resistance force, W = weight on wheel, C = tyre characteristic coefficient, D = outer diameter, h_t = tyre section height and w = tyre section width.

From this one can see how wheel geometry affects the rolling resistance of a specific wheel. Accordingly, one cannot assume that the 0.015 in a conventional car wheel is appropriate for smaller wheels found on the IP trolleys (the load as specified by GMSA) and the wheels to be used on the AGC. The C tyre characteristic coefficient is based on materials used and, in the case of the AGC and trolley, the same value will be applied. Assuming a standard 15" tyre with dimensions $D = 0.56$ m, $h_t = 0.09$ m, $w = 0.15$ m and a weight on each wheel of 3000 N, as well as an IP trolley's wheel with dimensions $D = 0.12$ m, $h_t = 0.045$ m, $w = 0.04$ m and weight on each wheel of 500 N the following calculations are performed.

First the equation is solved for C, using the maximum resistance coefficient of 0.021 and the characteristics of the 15" wheel:

$$\begin{aligned} C &= \frac{\mu_r \cdot D}{W} \cdot \sqrt{\frac{w}{h_t}} \\ &= \frac{0.021 \cdot 0.56}{3000} \cdot \sqrt{\frac{0.15}{0.09}} \\ &= 5.061 \times 10^{-6} \end{aligned} \tag{3.2}$$

Substituting this C value into the same formula, but using the IP trolley's wheel's dimensions gives a resulting co-efficient of friction value of:

$$\begin{aligned} \mu_{rTRLY} &= C \cdot \frac{W}{D} \cdot \sqrt{\frac{h_t}{w}} \\ &= 5.061 \times 10^{-6} \cdot \frac{500}{0.12} \cdot \sqrt{\frac{0.012}{0.04}} \\ &= 0.012 \end{aligned} \tag{3.3}$$

With a weight of 200 kg, the rolling resistance of the trolley totals:

$$\begin{aligned} F_{rTRLY} &= F_n \cdot \mu_{rTRLY} \\ &= (200 \cdot 9.81) \cdot 0.012 \\ &= 23.5 \text{ N} \end{aligned} \tag{3.4}$$

If the same calculations are done for the AGC, with the wheels being described by the following values $D = 0.2$ m, $h_t = 0.08$ m, $w = 0.05$ m and a weight on each wheel of 150 N, the following results are achieved:

Using the same C formula gives a resulting friction value of:

$$\begin{aligned} \mu_{rAGC} &= C \cdot \frac{W}{D} \cdot \sqrt{\frac{h_t}{w}} \\ &= 5.061 \times 10^{-6} \cdot \frac{150}{0.2} \cdot \sqrt{\frac{0.08}{0.05}} \end{aligned} \tag{3.5}$$

$$= \quad 0.005$$

With a weight of 43 kg (determined from the model of the AGC), the rolling resistance of the AGC is:

$$\begin{aligned} F_{rAGC} &= F_n \cdot \mu_{rAGC} \\ &= (43 \cdot 9.81) \cdot 0.004 \\ &= 2.11 \text{ N} \end{aligned} \tag{3.6}$$

The total resistance for the IP Trolley and the AGC combined is then 25.6 N ($F_{rTRLY} + F_{rAGC}$). This resistance applies only to the interface between the wheels and the ground.

3.2.2 Acceleration Force

The greatest force required will be to accelerate the AGC and the trolley. Once the system is moving only the frictional forces need to be overcome. To calculate the required force one uses the Newton's second law of motion (see Equation 3.7). Although acceleration is not completely constant, we will assume an average value to simplify the calculations.

The speed for the AGC was specified as a walking pace. From a few simple trials, 1.5 m·s^{-1} was determined. If we dictate that this must be achieved within 3 s, an average acceleration of 0.5 m·s^{-2} is needed.

The AGC was estimated to weigh 43 kg, this combined with the mass of the trolley (200 kg) we arrive at a mass of 243kg. The required force is thus:

$$\begin{aligned} F &= m \cdot a \\ &= 243 \cdot 0.5 \\ &= 121.5 \text{ N} \end{aligned} \tag{3.7}$$

3.2.3 Combined

From these calculations it can be seen that the required force during acceleration is the sum of all the forces at work during acceleration. These are the rolling resistance forces (F_r), the force required to accelerate the masses (F_a) and other frictional forces (F_m).

The last value mentioned comprises mainly of the mechanical friction in the bearing of the front castor wheel and the rear axle bearings. Other frictional losses in the motor and gearing are included during motor selection. According to SKF's bearing force calculator, for the given parameters the Total Frictional Moment came to 9.25 Nmm (SKF, 2015). With a wheel radius of 0.1m this equates to 0.1 N per bearing. Later design indicates two bearings per rear wheel, totalling 0.4 N. The bearing used in the front castor wheel was unknown, so a higher value of 0.5 N was used for it. This brings the total $(F_m) = 0.9$ N.

$$\begin{aligned} F_{T1} &= F_r + F_a + F_m \\ &= 25.6 + 121.5 + 0.9 \\ &= 148 \text{ N} \end{aligned} \tag{3.8}$$

Once the system is up to speed the force required to accelerate the masses is no longer required so the total pulling force required by the AGC is only:

$$\begin{aligned} F_{T2} &= F_r + F_m \\ &= 25.6 + 0.9 \\ &= 26.5 \text{ N} \end{aligned} \tag{3.9}$$

3.2.4 Traction

The amount of force applied by a wheel onto a surface is referred to as traction. While it is possible to select motors that can generate the required force, if the traction that the interface capable of is less than the torque needed, the wheels on the AGC will slip and movement may not occur.

To determine the maximum anticipated traction of the AGC, one looks at the coefficient of static friction (μ_s) between the wheel and the ground. Although the wheel is moving, the points on the ground and the wheel are stationary relative to each other. Should the wheel begin to slip, the coefficient of kinetic friction (μ_k) would become applicable.

The approximate model used for determining friction forces is that of Coulomb friction and is give by $F_r = F_n \cdot \mu$. The key factors are the normal force applied on the ground (directly related to the weight and weight distribution of the AGC) and the coefficient of friction.

In the case of a rubber/cement interface, the given co-efficient of static friction is $\mu_s = 1$ (Townsend, 2002).

To establish the normal force for the contact point one needs to determine the distribution of weight. For the purposes of the calculation it is assumed that weight is applied symmetrically across the width of the AGC. To determine the front/rear weight bias of the AGC its centre of gravity is required.

If the centre of gravity of the AGC is ascertained the weight on the individual wheels of the AGC can be calculated. The CAD model of the AGC was compiled specifying the correct materials for each component and, where a combination of materials was used, a

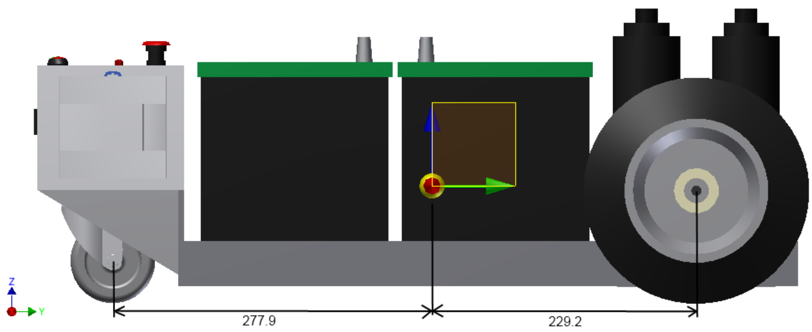


Figure 3.1: Centre of Gravity of the AGC Model

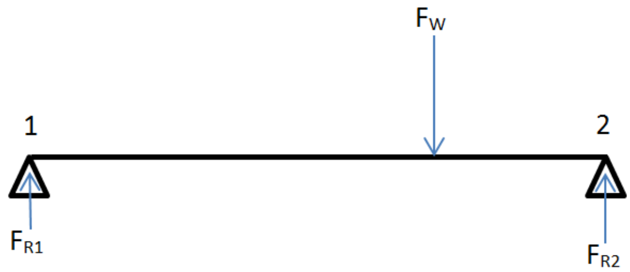


Figure 3.2: AGC Force Diagram

material was selected that provided a good estimate of the weight. In Autodesk Inventor Professional it is possible to have the software determine the centre of gravity of the object. This can be seen in Figure 3.1.

To calculate the force on each wheel one assumes a point load with two fixed supports. The model to determine this can be seen in Figure 3.2. The estimated mass of the AGC is $m_w = 43$ kg. Using a gravity approximation of $g = 9.81$ m·s^{-2} gives us $F_w = 421.8$ N

The sum of the moments around each point is then used to determine the resultant forces.

$$\begin{aligned} \sum M_1 &= F_w \cdot x_1 - F_{R2} \cdot (x_1 + x_2) \\ 0 &= 421.8 \cdot 0.2779 - F_{R2} \cdot (0.2779 + 0.2292) \\ F_{R2} &= 231.27 \text{ N} \end{aligned} \tag{3.10}$$

F_{R2} is the force applied by the driving wheels. Each wheel would apply 115.6 N on the ground.

$$F_t = F_n \cdot \mu_s \tag{3.11}$$

$$= 115.6N \cdot 1$$
$$= 115.6 \text{ N}$$

From Formula 3.11 one can see that the two wheels combined should be capable of applying 230 N. The total traction required for the AGC was calculated at 148 N (Equation 3.8), thus the wheels can provide sufficient traction for the AGC.

3.2.5 Measured values

With these calculated values in hand, it was possible to compare them with several measured values. At the GMSA plant one of the trolleys was pulled along a section of the route. Using a spring scale to pull the trolley is the researcher was able to read a value from the scale equivalent to the force required to move it.

When accelerating the trolley from a stationary position to the expected speed of movement, a maximum reading of 17 kg was noted on the scale. This was read when the 4 castor wheels were misaligned with the intended direction of travel. When the wheels were correctly aligned this value dropped to 10 kg. Once the trolley was up to speed, an average reading of 8 kg was recorded.

A digital push/pull gauge provided by GMSA was used to validate these results and similar values were noted. These equate to a required acceleration force of 167 N and a required constant driving force of 78.5 N. The 167 N value is noticeably more than the 100 N calculated force (for just the IP Trolley). The 78.5 N reading is also far higher than that calculated. This would lead to indicate that the rolling resistance calculations for the IP Trolley do not accurately represent the actual rolling resistance. The calculated value was 23.5 N, and in practice it is 78.5 N, this could be due to a number of factors, such as bearing friction or uneven surfaces.

The website *RobotShop.com* also has an online tool (Robot Shop, 2012*a*) which can be used to determine recommended motor specifications for a project. The calculator was given the following input values: M = 243 kg, 2 drive motors, wheel radius = 0.1 m, velocity = 2 m·s^{-1}, maximum incline = 5°, 24 V supply voltage, acceleration = 0.5 m·s^{-2} with a suggested efficiency of 65%.

From these values the website recommends motors with $\omega = 15$ rad/s ($\approx$ 143 RPM) and capable of providing $\tau = 25.3$ Nm, this equates to an effective pulling force of 253 N per motor. Or 506 N in total. This is far higher than calculated, primarily as a result of the 65% efficiency and 5° incline that was specified, but not included in hand calculations. This can easily be verified as follows:

The force comprises of two parts, the acceleration of the body (F_a) and the factor of the gravitational force that is relevant to movement up a slope, namely $F_g = m \times g \sin(\theta)$, with $\theta = 5°$ this equals 207.8 N. We've previously calculated $F_a = 121.5N$. The sum of these forces divided by the efficiency of the system gives us 506 N.

Setting the incline to 0° results in a recommended motor capable of supplying $\tau = 9.3$ Nm, equivalent to 186 N when a diameter 0.2 m wheel is used in conjunction with two motors. This is similar to the calculated value.

In summary, a required force of 167 N (measured) for accelerating the trolley, plus an additional 25 N (calculated) for accelerating the AGC would dictate the requirements for motor selection. This comes to a total of 192 N. An additional motor efficiency value is included later.

3.2.6 Motor

Motor Type

In Section 2.6 DC motors were selected were for use in the project. Key factors were price, size, control and reliability, with motor specifications such as voltage, torque and current requirements being considered here.

Standard brushed DC motors are used for a variety of applications. They are easy to control, are reliable and their power relative to price is advantageous. Brushless DC motors have similar attributes, but both the motors and controllers tend to be more expensive for equivalent products. However they do not have as many wear parts (i.e. the brushes), which can be seen as a benefit as it can minimise required maintenance. Wear of brushes is dependent on many factors including the speed, current and load the motor experiences, but an estimate of 7 500 hours is considered normal (Hamilton, 2000). 8 hours of driving, 5 days a week for 50 weeks a year comes to 2 000 hours, which means 7 500 hours equates to 3.75 years of operation. The cost of a set of brushes averages R200 per set. The cost difference does not justify the use of brushless motors in this application.

From the outset, considering initial budgets and cost analysis, it was understood that the high price of motors and controllers would be a major factor in conforming to the limits of the budget.

A supplier of DC motors was located through OE Coaches who supply DOGA DC motors. DOGA are a large Spanish company, well known in the automotive industry for the supply of wiper motors and the industrial standard of their motors bodes well for reliability in this application (DOGA, 2015).

DOGA have a very wide selection of DC motors. Usually they come pre-assembled with gearboxes making it is easy to find a motor to suit a specific application. Motors come in 12 V and 24 V varieties and several other design aspects are configurable.

Prices for the DOGA motors were cheaper than comparable motors from other local suppliers and considerably less than the equivalent servo and stepper motors. As mentioned previously, DC motor control is straightforward and motor controllers are readily available.

Motor Specifications

Power is often used as the main criterion to determine what motor to choose, but it does not necessarily follow that the required torque will be delivered at the correct speed. Torque and speed values should be assessed jointly. This is made easier by suppliers often displaying this information in the form of a torque vs. speed graph.

Another factor to consider is the operating voltage of the motor. DC motors are made to operate at voltages ranging from 1 - 100 DCV. For the automotive industry 12 V and 24 V DC motors are the most common.

To determine the required torque (T), two things are needed. Firstly the amount of force (F) the AGC must be capable of applying, and secondly the radius (r) of the wheel. They are related in the following manner:

The force is known from the calculations done in Section 3.2.3, and for previous calculations a wheel diameter of 0.2 m was used.

$$\begin{aligned} T &= F \cdot r \\ &= 192 \cdot 0.1 \\ &= 19.2 \text{ Nm} \end{aligned} \tag{3.12}$$

The combined required torque for the two motors is just over of 19 Nm, or 9.5 Nm per motor at startup.

A further consideration is the efficiency of the motor and the drive train. Because a motor manufacturer had not yet been chosen, and estimate for the efficiency was used. The Robot Shop specifies that DC motors can operate at an efficiency (η) of anywhere between 40 - 90% depending on the quality of the motor (Robot Shop, 2012*b*).

Further inefficiencies can arise in the form of gearing used to increase torque and slow down speed, as well as heat and friction losses. The Robot Shop estimates that an average drive train operates at only 65% efficiency. This value is supported by a project described by Brusamarello *et al.* (2013) which designed a system for low intrusion efficiency estimation that resulted in a similar average efficiency for the motors tested.

A gear train system operating at 65% efficiency would mean the required torque (T_r) would be:

$$T_r = {}^{T}/_{\eta} \tag{3.13}$$

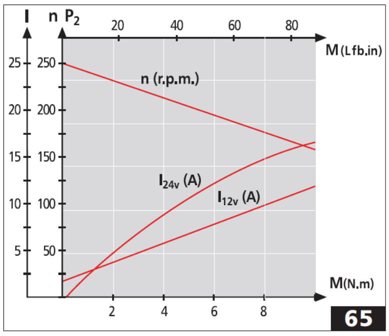


Figure 3.3: DOGA 319.9059.30.00 Motor Characteristics Graph (DOGA, 2012)

$$
\begin{aligned}
&= {}^{19.1}/_{0.65} \\
&= 29.5 \ \text{ Nm}
\end{aligned}
$$

This equates to 14.8 Nm per motor.

To determine the speed requirements one would have to consider the radius of the wheel together with the required linear speed of the AGC. The required linear speed was specified as 1.5 ms^{-1}. The variables are related by the following equation:

$$
\begin{aligned}
\omega &= {}^{v}/_{r} \\
&= {}^{1.5}/_{0.1} \\
&= 15 \ rad\ s^{-1}
\end{aligned}
\tag{3.14}
$$

$$
N = 143.2 \text{ RPM}
$$

Thus a motor which can supply 14.8 Nm of start-up torque and is capable of speeds up to 143 RPM is required.

Looking through suppliers lists of available motors a DOGA 319.9059.30.00 was selected because it displays the best balance of the required characteristics, see appendix F.1 for reference.

The selected motor had the following specifications: a nominal torque of 2.2 Nm at a speed of 230 RPM while drawing 4 A and a maximum (or start-up) torque of 20 Nm while drawing 30 A. The motor operates at 24 DCV, but no efficiency data is available. Other motors available with higher torque ratings operated at speeds which were too slow. A graph displaying the speed and current vs. torque of the motor can be seen in Figure 3.3. Motors running at 12 V were available, but the high power output of the motor relates to high current ratings. Higher currents require more expensive motor drivers and can result in quicker degradation of batteries (Doerffel and Sharkh, 2006). Therefore the researcher decided that the 24 V version would be the better choice.

The expected operating speed of the motor of 143 RPM is not depicted on the speed vs torque graph (Figure 3.3), but by determining the gradient of the curve, one can calculate that the expected torque delivery would be 11.4 Nm at this speed.

Although this is less than the required 14.8 Nm (Eq. 3.14), it is only needed during acceleration where the motor has more torque, closer to its maximum of 20 Nm. The 11.4 Nm is at its operating speed. At this speed it was determined that the motors need to apply 100 N (Section 3.2.5). This 100 N equates to 7.7 Nm per motor including efficiency calculations.

In summary, taken the motor efficiency into account, during acceleration (SF_1) the motor can deliver 20 Nm of torque (T_a), but the AGC requires only 14.6 Nm (T_r). Once up to speed (SF_2), the required torque is 7.7 Nm, and the motor can supply 11.4 Nm. These equate to safety factors of:

$$\begin{aligned} SF_1 &= \frac{T_a}{T_r} \\ &= \frac{20}{14.6} \\ &= 1.36 \end{aligned} \tag{3.15}$$

$$\begin{aligned} SF_2 &= \frac{T_a}{T_r} \\ &= \frac{11.4}{7.7} \\ &= 1.48 \end{aligned} \tag{3.16}$$

These safety factors are in addition to the bearing friction and efficiency factors already taken into account.

3.2.7 Motor Driver

Having decided on a motor, a suitable motor driver had to be chosen. A motor driver is required to control the voltage of and current flow to the motors. Using a dedicated controller comes with many advantages, which includes the protection of other electronic devices.

The selected motor runs at 24 V and its nominal current draw is 4 A with a start-up current of 36 A (DOGA, 2012). Because the AGC makes use of two such motors, either two motor drivers, or a single unit capable of supplying power to both motors would be required.

The DOGA motors chosen are commonly referred to as 'windscreen wiper' motors, because they are frequently used to power windscreen wipers. When used for this purpose the motors are driven in one direction by applying a positive 24 V charge and in reverse by applying a negative 24 V charge.

To achieve speed control of the motors one needs to be able to set specific voltages for the different motors. This is one of the functions of a motor controller. To achieve this it is necessary to communicate with the motor controller and this is usually done using an analogue signal: for example, where a voltage of 0 - 5 V would indicate a speed between full reverse and zero, and a voltage of 5 - 10 V would indicate a desired motor speed from zero to full forward.

Certain hobby kits also make use of the open RC controller protocol (Superdroid, 2012). A further option is to use a form of digital communication, using one of the serial protocols or, in certain instances, the CANBus communication protocol (Oßmann, 2009).

Most of the products researched fell into two main categories, those associated with the production industry, and those largely associated with hobbyists. Industrial products tended to be larger, have less functionality and be considerably more expensive than comparable products from the hobby industry.

For example Maxon Motors sell a single motor driver which can supply motors with up to 10 A (5 A continuous) for over R 4 000, with the version capable of 10 A continuous current costing over R 5 500 (RS Components, 2012*a*). A single unit measures 100 mm wide, 180 mm long and 25 mm deep, so finding space for two of these units on a relatively small AGV was difficult.

The best product that could be found which met the requirements was a Sabertooth 2x25 motor driver. This driver is very popular amongst hobby users (Robot Marketplace, 2012), and has also received praise for its reliability and ease of use (Post and Lee, 2011). The driver is capable of supplying a constant 25 A each to two DC motors and is capable of providing up to 50 A peak current for several seconds, such as during acceleration of the robot (Dimension Engineering, 2007).

The controller can receive data via a 0 - 10 V analogue signal, RC controls or RS232 Serial interface. It also includes several forms of thermal and over-current protection, which ensure that the electronics are not damaged, and also manages some of the control problems found when changing motor speeds. The controller is also capable of charging the batteries, providing power during the braking of the motors and includes lithium-ion battery protection. It can be powered from a source that supplies between 12 V and 24 V and includes a 5 V voltage regulator.

While the product cannot be sourced locally, even with postage and import taxes, the expected cost is R 1 600 for one unit capable of powering two motors individually. This product is considerably cheaper and more compact than locally obtainable industrial units.

One concern with this controller is its relatively unknown reliability. Product reviews did not create concern and it was felt that the size, price and capabilities of the Sabertooth unit in comparison to other available controllers warranted the choice of this product for prototyping purposes.

3.3 Power

In Section 2.7.1 three battery types were reviewed: lithium-ion, Ni-MH and lead-acid. Table 2.5 showed that while a lead-acid battery has a lower energy density and shorter lifetime than Li-Ion or Ni-MH batteries, they are considerably cheaper for equivalent energy requirements. Also, space and weight constraints are less important for this project than cost. Although a heavier battery does necessitate a stronger motor, the price of a larger motor would not be enough to counter the increase in cost that would be evident in the selection of a battery other than a lead-acid battery. The weight of the batteries in this design would constitute less than 20% of the entire system when towing the required trolley.

In industry the use of lead-acid batteries is common in similar applications, such as tuggers and forklifts (Kim *et al.*, 2011). Because of their high usage, lead-acid batteries are easily available at a reasonable price with a wide range of specifications. Furthermore, the standard 12 V rating of the battery is commonly used for electronics and motors, facilitating easy implementation into a project. Battery chargers are also readily available.

The system was designed to run off 24 V, the operating voltage of many industrial components. To achieve 24 V two 12 V batteries were used in series. Although lead-acid batteries can be obtained in 24 V and other voltages, the 12 V batteries are readily available at a competitive price, largely because of their wide use in automobiles. Any car service garage will keep stock of several standard size batteries, and the GM factory itself installs these batteries in all new cars they produce.

Raylite are a well-known producer of batteries in South Africa for the automotive industry, making batteries for a variety of applications. The batteries are distributed through Battery Centre and are available countrywide.

The company provides several options including hybrid, sealed silver-calcium and absorbed glass mat (AGM) batteries. Although each battery has benefits, the most commonly used is the sealed silver calcium. Particular benefits of this battery type over other lead-acid type batteries are:

- Higher charge rate acceptance;
- No topping up / no maintenance required;
- Low internal resistance; and

- 40% Longer life (Battery Centre, 2012*b*)

The battery chosen was a RayLite 638CNIS, two of which were purchased; the system was designed around these batteries. However, this decision was made early in the project, where two oversights occurred.

The first oversight was the use of a subset of lead-acid batteries commonly used in motor cars and referred to as starter batteries; deep-cycle batteries should have been selected in their place. The second oversight related to the capacity requirements of the AGC.

3.3.1 Deep Cycle vs Starting Batteries

Starter batteries are found in standard motor vehicles. They are able to supply high currents for short periods of time, and are generally kept at a high level of charge. Deep-cycle batteries are designed to provide a constant low-current over an extended period of time. It is expected that they be used until relatively flat and then recharged to full capacity on a semi-regular basis.

While both battery types make use of the same chemical reaction to provide power, the major difference is the lead content. Deep-cycle batteries contain larger lead panels to allow for a higher degradation over the extended usage time expected of them. This higher lead content results in a higher cost for deep-cycle batteries of around 70%. It also results in a slightly larger and heavier battery for the same Amp-hour rating.

The constant high proportion charge/discharge cycles in a starter battery would degrade the battery's lead pads to such an extent that the chemical reaction would no longer be possible. Thus in this type of project a deep-cycle is preferable because of the higher number of cycles through which they can charge. The use of deep-cycle batteries for similar applications, such as in forklifts, tuggers and golf carts, is well understood and many companies offer contracts to manage the maintenance of these batteries.

It was not possible to make the upgrade to the deep-cycle batteries for this project, and all testing was done using standard starter batteries. The main effect this would have is on the long-term performance of the batteries. In addition, should similarly rated deep-cycle batteries be used, the physical dimensions and weight of the entire system would increase, necessitating some redesign.

3.3.2 Energy Requirements

Calculations were performed to determine the energy requirements to run the system for an 8-hour shift. The main draw on the system would be the motors, but all the associated electronics would also require constant power.

Table 3.1: Basic Electronic Energy Requirements

	Current (A)	Voltage (V)	Power (W)	Energy (8 Hours) (Wh)	Battery Requirement (Ah)
PLC	0.2	24.0	4.8	38.4	0.2
5 Ind Sensors	0.1	24.0	1.2	9.6	0.1
3 Prox sensors	0.0	24.0	0.7	5.8	0.0
Wireless	0.1	3.3	0.2	1.8	0.0
Lights	0.1	24.0	2.4	19.2	0.1
Remote receiver	0.2	24.0	4.8	38.4	0.2
rfid	0.1	5.0	0.5	4.0	0.0
Miscelaneous	0.6	24.0	14.4	115.2	0.6
				Total	**1.2**

Table 3.2: Energy Requirements for a Shift

	Acceleration		Rolling Resistance		Mechanical Force		laps	Energy
	Force (N)	**Distance** (m)	**Force** (N)	**Distance** (m)	**Force** (N)	**Distance** (m)		(J)
With Trailer	121.5	5	25.61	50	30	50	120	406 560
W/o Trailer	21.5	5	2.11	50	30	50	120	205 560
					Total			612 120 J 170.0 Wh 7.1 Ah

The PLC, sensors, wireless modules, lights and other miscellaneous items would require roughly 1.2 Ah combined (Table 3.1).

Instead of looking at current draw during the process, because many of the calculations had already been done, the researcher used the estimated power requirements from a force perspective, and looked at the total energy requirements of the system.

Table 3.2 shows the three main forces that need to be overcome and uses the values calculated in Section 3.2 to total the amount of energy required for a lap. Half the lap is completed with the trailer, and half without it. For each force, the distance that it is required to act over is used to determine the energy requirement from $W = F \times s$. This value is multiplied by the number of laps to be completed in a shift to give total energy requirements for the batteries.

The total calculated is 612 120 J, equivalent to 170 Wh. Given the 24 V rating of the batteries, this would equate to 7.1 Ah. This plus the 1.2 Ah for the electronics results in a 8.3 Ah batter requirement. As discussed earlier, a Raylite 638 battery was selected, with a capacity of 60 Ah which far exceeds the calculated requirements for the AGC. The

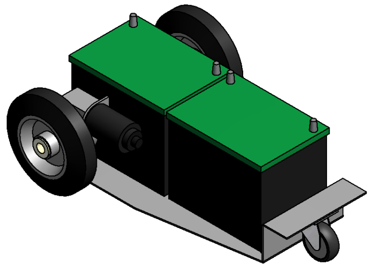


Figure 3.4: Initial Body Concept

decision was made prematurely without a full understanding of the energy requirements; however these batteries were used in the rest of the design.

3.4 Body

GMSA requested that AGC's body be designed to use a simple frame with several parts that could be welded together easily and a minimal number of nuts and bolts for assembly. The design should be neat and enclosed as much as possible, while still allowing easy access to critical components.

The setup chosen was a three-wheel configuration, with the two driving wheels and motors located at the back of the AGC and a single, front-mounted, rotating castor wheel to support the front. A three wheel setup negates the use of suspension and placing the driving wheels at the back of the AGC means that when a trolley is attached, the extra weight increases the traction on the driving wheels. The dimension restraints given to the height (0.5 m) and the width (0.4 m) would determine the overall size of the AGC.

The two lead-acid batteries would consume the largest volume of the AGC. The dimensions of the selected battery were 241x173x215 (lxwxh mm) (Battery Centre, 2012*a*). This imperative was the starting point for the AGC design.

The initial design conceptualised the batteries lying lengthwise along the centre of the AGC with a motor lying flat on either side of the back battery. This can be seen in Figure 3.4. Although ideally the batteries would be placed over the driving wheels as in this example, it transpired this was not possible because the space required for the motors and bearings to support the wheels was too great. Therefore the batteries were placed in the middle of the AGC, just in front of the motors. The initial layout can be seen in Figure 3.5 which includes the motors previously selected and bearings.

A 'cradle' to hold the batteries keeps them in place, and allows them to be removed easily should switching be required on a regular basis. A small castor wheel is mounted to the front, and to the rear space is given for the motors and bearings, with the wheels located just to the sides.

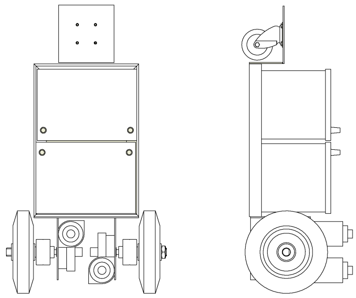


Figure 3.5: Initial Body Design, Top and Side Views

This was the basic design used to facilitate calculations.

3.5 Navigation

One of the most crucial features of the design of an AGC is the navigation system. As discussed in the literature review, the researcher concluded a line-following system would provide the best reliability and cost for the project. Section reflinesens outlines the decision that an induction sensor based system would be used.

3.5.1 Sensors

The type of induction sensors to be used in this particular environment had to be identified.

In the case of proximity sensors there is little difference in the products offered by the major manufacturers. All the products will respond in the same way, be of similar price and conform to the same environmental operating standards.

As other Telemecanique products had already been selected the researcher decided to secure induction sensors from the same source. The product finder on Schneider Electric's website was used to determine the correct unit (see appendix F.2 from the catalogue). A plastic sensor with 3 wires, a discrete NPN output and cable electrical connection was requested. A sensing range of 16 - 24 mm was chosen.

The recommended sensor was a Telemecanique XS230AANAL2. It has a barrel form of diameter 30 mm, which is threaded, and has an optimal sensing range of 22 mm. This would allow enough space for irregularities in the ground surface and small objects to pass under the sensors without affecting them.

3.5.2 Control

The next step in the navigation system was processing the input from sensors to determine the required output values to the motors. The simplest method is to use only two sensors. If the left sensor is activated the AGC is instructed to turn left, if the right sensor is activated the AGC is instructed to turn right.

The addition of more sensors allows for a greater resolution, which in turn increases the AGC's locational awareness. Increased resolution facilitates better control of the system. It would be necessary to determine the number of sensors required for acceptable control, while minimising cost. As mentioned, two is the minimum required number of sensors. A third sensor provides the option of driving in a straight line as opposed to the constant, left or right correction of a two-sensor system.

Makrodimitris *et al.* (2011), in their design of an education line-following AGC made use of just three sensors. The maximum speed for their robot however was 0.32 $\mathrm{m{\cdot}s^{-1}}$. It was expected that the higher maximum speed of the subject AGC would increase its instability. To overcome this, the researcher decided to use an extra pair of sensors. Modelling and testing would enable the determination if this was sufficient or if extra sensors would be required.

A common form of control is the PID controller. The main factors considered by the controller are the object's current position (process variable), its desired position (setpoint) and the controller's output (manipulated variable), in this case the variable that would control the motors. The difference between the process variable and the setpoint is referred to as the error, and should be reduced to the minimum.

The controller processes the error through three phases to determine the best value for the manipulated value, to achieve the setpoint.

The first phase makes use of the proportional (P) factor which interfaces with the instantaneous error of the system. If the error is high, the output will be high, and if the error is low the output will be correspondingly low. The integral (I) factor assesses the sum of the error over time and calculates the total error that should have been corrected. The derivative (D) factor assesses the rate of change of the error to alter the output.

When setting up a PID controller one specifies multipliers for each of the PID elements. By adjusting these multipliers one is able to tune the controller for optimum control. Although other forms of controllers are available, PID is the most commonly used in industry. Furthermore, many PLC units come with built-in PID controllers, which make for easy setup and use.

3.6 SCADA

There are two main ways to interface the SCADA system in this project. The first method, where the AGC monitors its position relative to a fixed marker, places the hardware on individual AGCs and makes use of a wireless system to communicate with a central server. The second places the hardware on the ground. It can be connected either wirelessly, or wired to the server, and monitors the movement of AGCs relative to itself.

For this project it was considered preferable to contain everything within one unit. This, linked with a wireless unit facilitates the modifying of tracks and circuits, and removes certain obstacles created by placing the hardware on the floor.

Preference for the SCADA system was influenced by the fact that it will allow one access to an overview of the current state of the system. The relay of the exact position of each AGV is not needed but regular updates should be easily visible.

The idea is to use a set of markers to give the AGCs locational awareness and that this data is transmitted, possibly along with other information such as running state, to server unit. This unit will store all the information it receives in a database which can then be accessed from a remote terminal.

3.6.1 Markers

In selecting markers an RFID solution immediately came to mind. The system is found throughout society, most often in access cards for buildings and for small transactions such as the Oyster Card used in the London Underground (Hadjileontiadis, 2008).

The marker itself is most commonly a small microchip with an antenna that is mounted in a thin plastic casing, often resembling a credit card, but different forms are available. An RFID reader consists of a small circuit with an antenna. When the RFID chip is within proximity of the RFID reader, it receives power via an induced current in the antenna and will respond by communicating its unique ID to the RFID reader.

The system does not require contact to function, and can work with air gaps exceeding 2 cm. The cards are robust and the system straightforward to implement. RFID cards are relatively cheap and easy to acquire, and therefore could be placed as required without concern regarding financial impact. In the event of damage or loss, they can be easily replaced.

3.6.2 Wireless

To establish communication between the AGC and the server some kind of wireless system was required. The choice of wireless device was also dependent on the controller selected.

Table 3.3: Wireless Decision Matrix

	Cost	Range	Complexity	Stability	**Total**
Wi-Fi	3	3	2	3	**11**
Bluetooth	3	3	3	3	**12**
ZigBee	4	5	4	4	**17**

In Table 3.3 shows the elements used to select the best wireless communication system taking into account the type of controller used.

The most common wireless system is Wi-Fi, the standard wireless communication protocol found in laptops, cellphones, tablets and other devices for connecting to local area networks (LANs). Many products are available covering a wide range of applications and scales. It is also integrates well with existing Ethernet networks, wired or wireless. However, Wi-Fi networks require additional infrastructure relating to network management, but often this can be incorporated into existing networks. Almost all computers (x86 based architecture) purchased today will come with the hardware to access either a wired or wireless Ethernet network. PLCs also regularly come with wired Ethernet ports for connectivity to Profi-net or similar networks.

Bluetooth is another well-known, commonly found wireless technology. Although it is capable of distances up to 100 m, communication is generally only used on a small scale for communication with devices < 10 m away. Bluetooth also has many security elements built in, such as the pairing of devices and passcodes. While appropriate in some applications, these will make a moving, reconfigurable system difficult to maintain. Bluetooth networks are ad-hoc networks, not requiring additional infrastructure apart from a connectivity device for each element wanting to connect

The Zigbee protocol was developed several years ago and is becoming increasingly popular in commercial products. The protocol operates in the 2.4 Ghz range, similar to standard Wi-Fi, but is designed for low-power situations, where less data is required to be transferred (Willig *et al.*, 2005). From the Zigbee protocol the company Digi developed a range of small wireless units named the XBee range. Standard versions have a range of up to 100 m unobstructed, and the Pro version can communicate up to 2 km (refer to appendix F.3). XBee units can be setup for different types of networks, but by default they broadcast to all other units within range (ad-hoc). They have several digital and analogue I/O ports as well as a serial TX and RX line.

From Table 3.3 we can see that based on the requirements for the project the Zigbee protocol is the obvious choice. While Wi-Fi and Bluetooth are capable of far more, have far higher bandwidth capabilities as well as security features, none of these factors are specifically relevant to the application at hand.

3.6.3 Server and Client

SCADA systems vary according to their application. The basic premise is the development of a method to monitor a system so problems can be identified quickly and be corrected. Good systems also record data for later analysis, to help to identify problem areas and optimise systems.

The easiest way to store data is in the form of a database. Common databases make use of a SQL command structure for interacting with the database. Several commercial products are used (for example MSSql), but free ones such as MySQL are also available. The common structure facilitates programming; for example it is quite easy to program for one database and, by merely switching the library, a different database type can be used.

The researcher, based on his prior experience with SQL databases decided this would be the best way to structure the SCADA system. Databases offer a further advantage in that all data can be recorded for later referral, or to provide current system information.

Client custom software can be designed for a front-end. However to make it more accessible across various platforms the researcher decided to use a web interface. This makes accessing the client from other networked devices easier, and the data can be viewed from almost any platform, for example cellphone, tablet or computer.

Client custom software can be designed for a front-end. However to make it more accessible across various platforms it was decided to use a web interface. This makes accessing the client from other networked devices easier, and the data can be viewed from almost any platform, smartphone, tablet or computer.

3.7 Controller

3.7.1 Requirements

From the previous design decisions it was possible to compile a list of controller requirements:

- DC Powered, 24 V available
- 10 Digital Inputs: sensor and button monitoring
- 4 Digital Outputs: lights and other notifications
- 2 Serial Ports: interface with RFID and wireless transmitter

And for communicating with the motor controller either:

- 2 analogue Outputs or

- 1 Serial port

3.7.2 Specific Choice

In Section 2.5.4 different controller types were discussed, and the decision was made to use a PLC.

There are many manufacturers of PLCs: some of the main contenders are Siemens, Alan Bradley and Telemecanique. Often industrial companies have partnerships with PLC producers, where all newly-installed hardware will be from a specific supplier. In this way inventory can be minimised by stocking only one manufacturer's goods for various machines or systems. Personnel can be trained in one company's products and better relationships can be built with suppliers and support staff at this company.

Although GM International makes use of the Alan-Bradley range of PLCs, GMSA has mainly installed Telemecanique (a Schneider Electric range) units (Norman, 2012). For this reason the researcher decided to investigate the options offered by Telemecanique. Their main controller ranges are Modicon (Quantum, Premium and M340), Twido and Zelio. The Modicons are described as mid-range to large PLCs for process applications and the Zelio as a smart relay system.

The Twido range is separated into two components: a modular set where one buys the CPU and the required I/O pieces individually, and a Twido set which combines the CPU with a set number of digital I/Os and optional expansion ports.

After investigating the alternatives, the Twido appeared to be the best choice. It was well priced in the PLC range, is fairly small and easy to wire. The data sheet (see Appendix F.4) specifies either a 24 VDC supply or 110 VAC and the choice of a unit with 40, 24, 16 or 10 I/Os. The 24 I/O unit was chosen for its capacity to sink or source 24 V for 14 inputs and 10 relay outputs. It can support up to 4 expansion ports including RS232 and analogue output modules.

Furthermore it features PID controllers which could be used for developing a controller for the steering.

3.7.3 Problem with Controller

On receipt of the controller a problem was identified. The PLC was listed as supporting four communications ports. These were intended to be used for three serial ports, for the RFID, the wireless and for the motor controller. However once the hardware arrived it was noted that only two of the four communications modules can be serial ports; the others can be CAN, GPRS modem or Ethernet.

Of the two serial ports available one of them is a fixed RS485 port (RS232 was required for the other devices) and although this port could be used during operation, it was also used for programming and, as such, it would be impossible to operate the robot under normal circumstances while monitoring the program from a computer.

To prevent further delay it was decided that the PLC would be used but that only the motors would be controlled from the PLC itself. A separate plan would have to be made for the RFID and wireless. One of the RS232 serial modules was installed and the RS485 module was left open for programming and system monitoring.

3.8 Proximity Sensors

In addition to the induction sensors, it was also necessary to build a system to alert the AGC of an impending collision. Ideally the AGC would stop before a collision occurred, but should it fail to do so, a further safeguard was required.

Several proximity sensors are available to identify obstructions from a distance. The main ones to consider are IR, ultrasonic sensors, and scanning laser range finders. All of these sensors have been mentioned earlier.

Laser range finders would have been the preferred solution as they offer a much wider detection range and are more accurate. Unfortunately this was countered by the extreme cost. A small, low-end unit (Sick TiM310) was quoted at R 10 927 (Rubicon Electrical Distributors, 2012). This alone excluded this sensor from use in the project.

Therefore the researcher decided to mount three IR sensors on the AGC facing forwards to provide some form of proximity detection. A Schneider-Electric XUB5ANANL2 IR sensor was chosen (its datasheet can be seen in Appendix F.5). The sensor has a sensing range of approximately 0.8 m, as this gave the AGC enough time to stop before a collision would occur, assuming the obstruction was stationary. The sensors had a very small viewing angle, less than 10°, but three of these placed next to each other was able to cover the required front area of the AGC.

A bumper unit was also placed at the front of the AGC. This would act as a sensor and stop the AGC, would also provide some protection to the AGC, especially the sensors mounted at the front.

A sheet of perspex was cut to size and curved to form a protective barrier at the front of the AGC. It was mounted on two metal dowels which activated switches when depressed. The depressing of the bumper switches would have the same effect as activating the emergency stop button.

3.9 Additional Components

Several additional components were required for the effective operation of the AGC, such as buttons, lights, and wiring.

A main power switch for the entire unit was required, capable of handling high currents, potentially over 50 A DC, because of the current draw from the motors. Finding suitable switches at a reasonable price was difficult as most switches give only AC ratings. Ultimately a 3-phase AC switch presumed capable of handling the required current was chosen.

An emergency stop button was also required. Although it is quite easy to set up a software stop to monitor the button and stop sending commands to the motor driver, this is not as safe as allowing the emergency stop to actually cut power to the motors. Certain motor drivers have enable lines which can be cut to stop them working, but unfortunately the selected model did not. It was very difficult to locate an emergency stop button capable of handling the high currents drawn by the motors. Thus the emergency stop switch, when not activated, drives a relay providing power to the motors.

General stop and start buttons were selected to act as inputs to the controller. Two small buttons, red and green to symbolise stop and start actions respectively, were selected.

Two lights were required to indicate the current state of the AGC. Red and green 24 V LEDs were chosen for this task. They are similar in size to standard fuses and comprise several surface mounted LEDs.

The table provided by Cables & Connectors, Inc (2012) was referenced to determine the correct gauge of wires to supply the required current to the motors, which gives expected allowable currents for given gauges of wire. For currents up to 73 A an 8 gauge wire was recommended. This equates to a wire, or strand of wires with a combined diameter 3.26 mm.

Datasheets for the relevant components discussed here can be viewed in Appendix F.6.

3.10 Quality vs Price

Research for this project involved the scrutiny of numerous suppliers of sensors and other equipment. Much of the equipment used in this project is designed for use in the industrial environment and as a result had high IP ratings (related to ingress protection) concomitant with high cost.

Alternative, cost-cutting options are available for the design of low-cost AGVs. IR sensors like those used in this project can be had at a tenth of the price, microcontrollers could be used in place of a PLC, and several other shortcuts could be used to significantly decrease the expected cost of manufacture. However, these could lead to other problems, especially relating to quality.

Many of the cheaper versions of required components are not supplied by reputable manufacturers and the quality and reliability of these products is questionable. Finding replacements in the future could become difficult. It is evident that the pursuit of cutting costs could well prove problematic in the long term, considering the amount of time and energy that would be required to maintain a unit in working order.

It is important for GMSA to review the budget limit of R 35 000 per unit if they wish to use these units on a production basis.

Chapter 4

Final Design

This chapter reviews decisions made for the final design of the project. It uses the research and calculations documented in previous chapters to determine the most suitable choices for different aspects of the project; validates the support for each decision; and demonstrates some of the more advanced design procedures.

4.1 Navigation and Drive

As discussed in Section 3.5 the method adopted to navigate the AGC comprises a line-following system whereby a pre-laid metallic strip is used to indicate the track that must be followed. An array of several induction sensors is used to determine the AGC's position relative to the track.

The sensors give a discrete output as they either detect the track or they do not. As such the resolution is limited to the distance between sensors, with some overlap. It was decided that a PID controller would be incorporated to obtain the best control. However, several factors made this difficult.

4.1.1 Modelling

To test various methods of control for the AGC, a simulation environment was modelled. This way different control methods could be implemented relatively easily, and the way they responded to the environment could be observed without having to program each method onto the AGC's controller.

First we look at the physics of the differential drive system. When both the motors are running at the same speed, the robot will travel in a straight line at the speed set by the motors. When only one motor is running, the AGC experiences a rotational velocity around the stationary wheel. When both wheels are moving, and a speed differential is

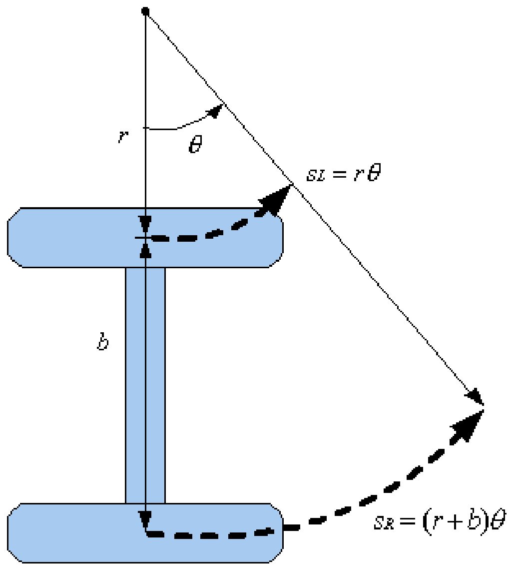


Figure 4.1: Dimensions Used for Modelling Lucas (2001)

apparent, the point of pivoting moves outwards on the side of the slower wheel; the point also moves dependent on the magnitude of the speeds, not only their differential. This setup illustrated in Figure 4.1.

It is thus possible to fully define the state of the robot when the dimensions of the robot are known and the speed of the individual wheels is known. Because the speed of the wheels is a controlled value and the dimensions of the robot are set, we are able to continuously recalculate the robot's state. If we assume the robot's individual wheels rotate at a constant speed for a set time, it is possible to calculate the change in angle that would occur in the robot, as well as the displacement the robot undergoes as a result of the wheel movement. By recalculating these values for decreasing timesteps it's possible to approximate the movement of the robot. The smaller the timestep used, the more accurate the model of the system will be.

Several timesteps were tested, and after the value was decreased below 0.005 s, minimal improvement was noted in the simulation results.

To simplify the calculations, a maximum acceleration was set for the motors. This value was determined from selection criteria defined in Section 3.2.2 and was initially selected to ensure that torque requirements for the motors would be sufficient to overcome any forces acting on the robot. We thus preclude any force calculations from our model, assuming that at the specified acceleration the robot will have sufficient torque to allow the model to give a fair representation of the robot's real-world kinematics.

To model the drive system we use the setup shown in Figure 4.1. From this model formulae can be derived for the x and y position of the AGC at different points in time. The formulae set out in Equations 4.1 to 4.3 were derived by Lucas (2001) and provide x

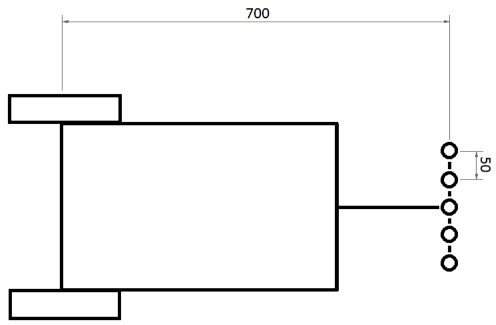


Figure 4.2: Layout of Sensors Relative to AGC

and y coordinates for the AGC after a set time t where x_0 and y_0 are the original starting coordinates of the AGC. v_R and v_L are the speeds of the right and left hand wheels in m·s^{-1}.

$$x(t) = x_0 + \frac{b(v_R + v_L)}{2(v_R - v_L}(\sin((v_R - v_L)t/b + \theta) - \sin(\theta)) \tag{4.1}$$

$$y(t) = y_0 - \frac{b(v_R + v_L)}{2(v_R - v_L}(\cos((v_R - v_L)t/b + \theta) - \cos(\theta)) \tag{4.2}$$

and for the angle

$$\theta(t) = \frac{(v_R - v_L) \times t}{b} + \theta_0 \tag{4.3}$$

To simulate this model, the variables were modelled in a Matlab script. The script was set up to allow control of the environment from the perspective of time, setting of maximum speeds and accelerations as constrained by the motor's specifications as well as the line to follow. The script initialises by setting a time frame through which to run and a timestep to calculate the progressive coordinates and direction of the robot. Each iteration within the script progresses the robot one timestep which recalculates its next position and direction.

After the environment was correctly simulated, control of the system was added. Control is based on the position of the 5 induction sensors relative to a predefined line. Control via both a straight line, defined by the standard $y = mx + c$ equation, and a parabola of the form $y = ax^2 + bx + c$ was given. In this way the movement along a straight line and round a corner could be tested.

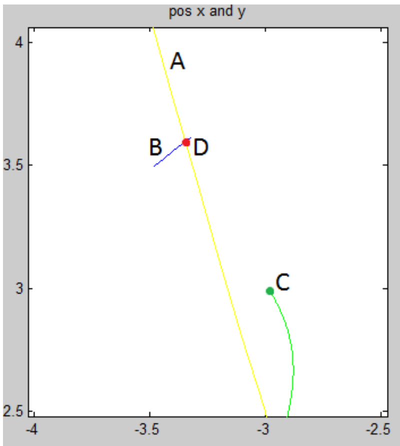


Figure 4.3: Image Explaining Simulation Calculations

Explanation

To get positional feedback, five induction sensors are used, modelled as per the design of the AGC (Figure 4.2). The sensors spacing of 50 mm was as close as the sensors' specification allowed without interference occuring. Simulation results were visualised in diagrams such as Figure 4.3. In this diagram the line A indicates the track that must be followed. The point C shows the current position of the AGC (the centre-point between the two driving wheels) and the corresponding green line its previous positions. The blue line B shows the position of the five sensors on the AGC with the ends of the line corresponding to the positions of the first and fifth sensors in the array. Point D is the point where the track and the line of sensors intercept. This is deemed to be the desired location of the AGC for the model.

When the parabola is being used, two possible points occur; these are compared and the one that is farther away is discarded, as well as any non-real results.

For control purposes, calculations requiring the position of the AGC make use of the position of the centre sensor at the front of the AGC rather than to the location between the two driving wheels, which is used for positioning calculations. This is because positioning calculations need to make use of the point between the two driving wheels, but control of the AGC is based on the position of the sensors to the line it is tracking. The point D doubles as the reference point for determining whether any of the sensors are active. The point D is then compared to the position of each of the five sensors in the array. The sensor that is closest to point D then becomes the active sensor, assuming this distance is less than 20 mm (the active area of the sensor). If the value is greater than 20 mm, then the active sensor doesn't change from its previous value.

However, this model excludes the real-life extreme situation where both sensors could become active at once. For this to happen the AGC would have to be travelling at an angle exceeding 60°; this shouldn't happen during normal operation, but it was taken into

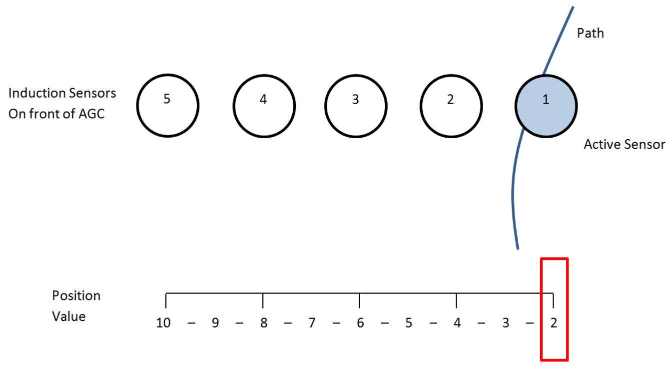


Figure 4.4: Sensor Layout with Single Activation

account in the PLC programming.

Linear Steering

Initially a basic linear steering method was planned. The AGC makes use of five induction sensors to get an indication of its position relative to the line it is supposed to be following. Depending on which sensor is active it is known in which direction the AGC needs to turn to remain on the path. Figure 4.2 shows the sensor positions relative to the AGC. For each sensor that can be activated there is a set speed for the two driving motors. In Figure 4.4 sensor 1 has been activated, this means the AGC is too far to the left of the line and must turn to the right; to do this motor on the left must turn faster than the motor on the right.

There are effectively five set positions for the AGC. When sensor 3 is active, the AGC proceeds in a straight line at a set speed. If sensor 4 or 2 is activated, the right and left motors speeds are increased respectively. Should sensor 5 or 1 become active, the outer motor's speed is increased, while the inner motor's speed is decreased.

However unlikely, should two sensors be activated simultaneously, then an average value for the position of the line is given. Because the PLC works best with positive integers, a range from 2 - 10 in single increments is allocated to the sensors, with 6 being the desired position. In Figure 4.5 one can see how both sensor 3 and 4 have been activated and a value of 7 has been assigned to the position. For each of these in-between values, the speeds of the motors are set to halfway between what they would be for each of the neighbouring sensor values.

It can happen that no sensor is active, for example when the line is between two sensors or the AGC is no longer on the line. Should this occur, the AGC continues to respond as if the previously active sensor is still active. To illustrate, when the path veers right and the AGC doesn't turn sharply enough to follow the track, it will continue turning to the right until it regains the line, even though no sensor is active at that time.

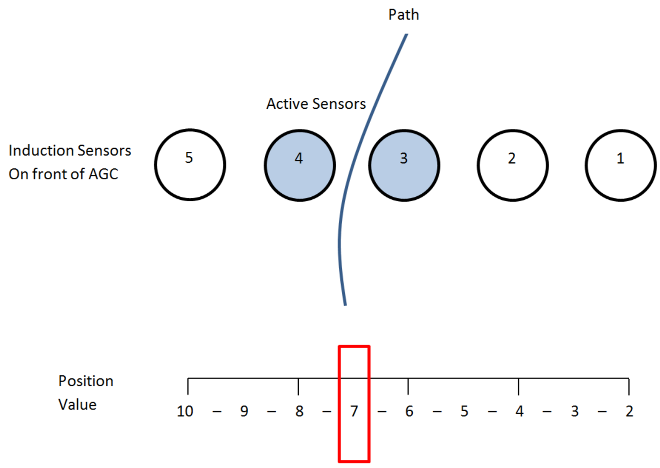


Figure 4.5: Sensor Layout with Double Activation

This mode of control was the initial format used for testing the simulation.

Results of Simulation

Figures 4.6 to 4.9 illustrate the results of simulations using different criteria. For all simulations on the plot of the x and y coordinates of the AGC, the x and y position is of the middle point between the two driving wheels. The blue marker indicates the start point of the AGC. The blue line is the path the AGC followed. The red line is the line the AGC should follow and the short blue line is the final position of the sensors at the end of the simulation. The second graph shows the orientation of the AGC, and the third graph indicates which sensor is active at any time. Should no sensor be active, the previous value is maintained.

The first set of simulations was run using only the straight line. At relatively slow speeds (60% of desired running speed) control seemed fairly stable (Figure 4.6). The robot was generally able to follow a straight line pivoting only between the inner three sensors after it stabilised and with an orientation variation of less than 4°. The distance of the 0 point of the robot to the desired position remained within 3 cm of the line. The position of the centre sensor to the line remained within 6 cm.

At higher speeds, nearing the desired speed of the robot, the robot was still able to follow a straight line (Figure 4.7), but the pivoting became more pronounced as the robot had to accelerate up and decelerate down to higher and lower speeds, causing a high amount of overshoot on the steering. The result was an orientation variation of 15°, with the centre sensor getting up to 10 cm away from the line. The 0 position of the AGC remained with 5 cm of the line. At this speed an oscillation was approximately 0.4 s long. The high speed of the oscillation and the high frequency made the AGC's movement appear erratic.

When navigating a corner, the AGC responded in a similar fashion at both low and high

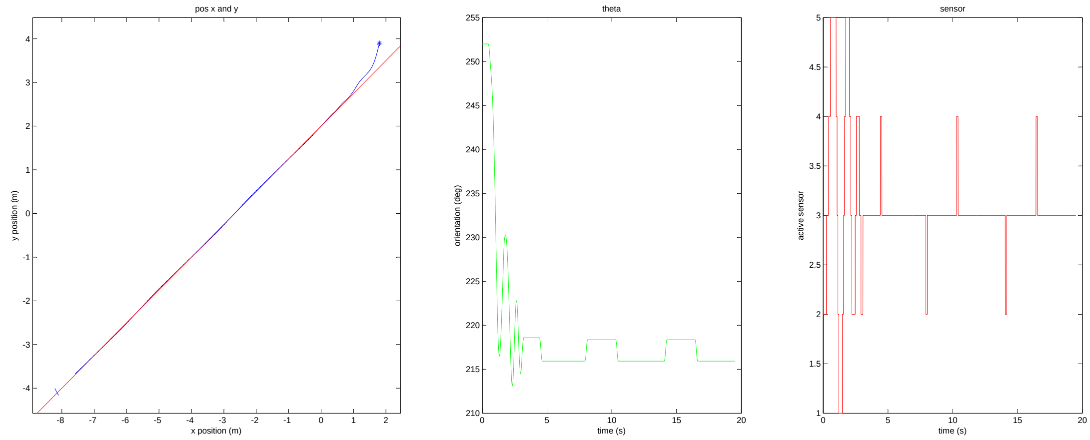


Figure 4.6: Simulated Linear response of the AGC at Low Speeds

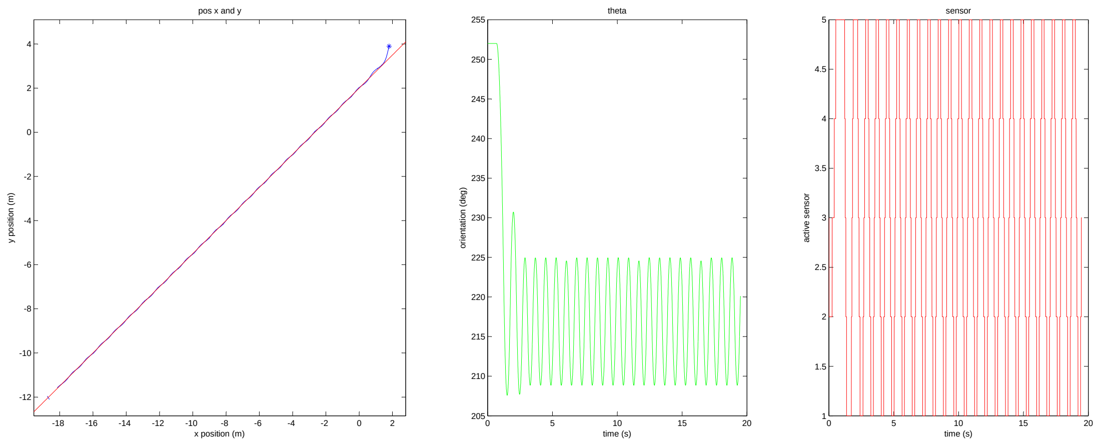


Figure 4.7: Simulated Linear Response of the AGC at High Speeds

speeds (see Figures 4.8 and 4.9 respectively). Although at points it was up to 20 cm off the track, it stabilised on the outer end with a deviation of less than 3 cm at both high and low speeds.

PID Control

In order to improve the line-tracking capability of the AGC the researcher decided to implement some form of control system. The linear system of steering initially tested was basically a proportional controller, taking into account only the difference between the current and desired positions. The obvious next step was to expand this to a PID controller. A major benefit was due to the PLC's inclusion of preprogrammed PID controllers. Although other types of control are possible (e.g. fuzzy logic or genetic algorithm), the complexity of the systems make them difficult to properly integrate into the PLC with its limited programmability.

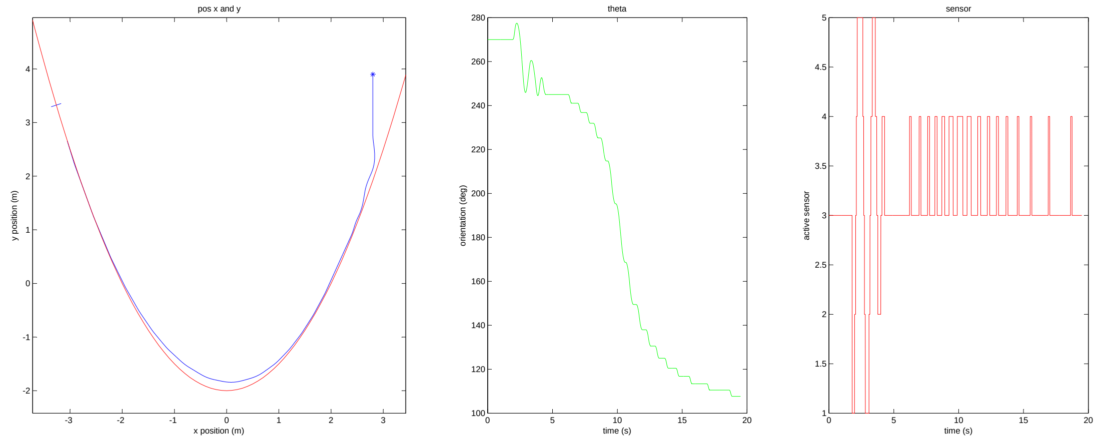


Figure 4.8: Simulated Linear Response of the AGC at Low Speeds Round a Corner

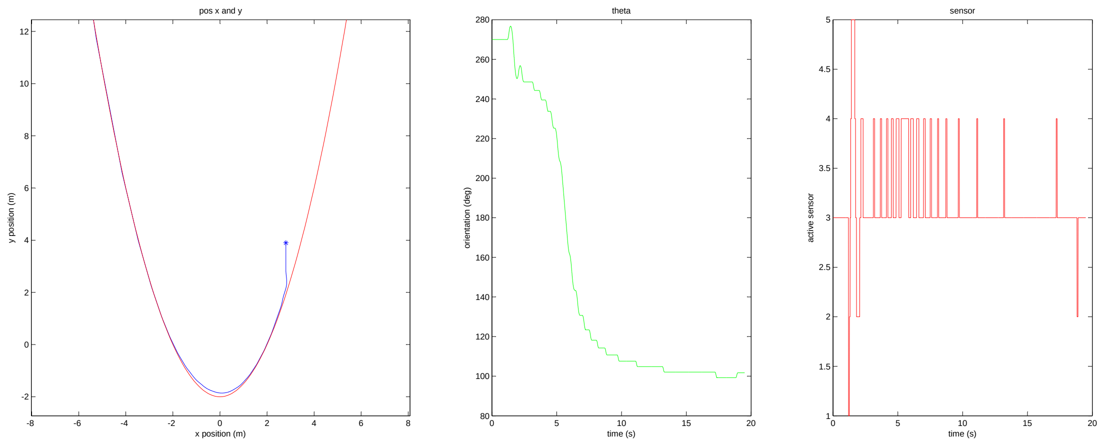


Figure 4.9: Simulated Linear Response of the AGC at High Speeds Round a Corner

A separate PID controller was configured for each wheel; they both react to the same variables and alter their outputs accordingly, which directly controls the speed of the driving motors. The biggest problem foreseen with this solution was the low resolution. It was uncertain whether the PID control would improve the AGC performance by any notable amount.

Firstly K_P (proportional gain) was adjusted to get stability in the system. The identified value was 0.1. A higher value resulted in the AGC turning on the spot; a lower one and the AGC would not react quickly enough to sensor changes. Figure 4.10 reflects the movement of the AGC with $K_P = 0.1$ and all other gains set to 0. An angular oscillation of about 15° is noted. This is higher than when the AGC is run at low speeds in a linear manner, but lower than at high speeds. The resulting average speed was also in between that of the AGC when run linearly at high and low speeds.

Thus the response is similar to that of our linear controller. From the response seen

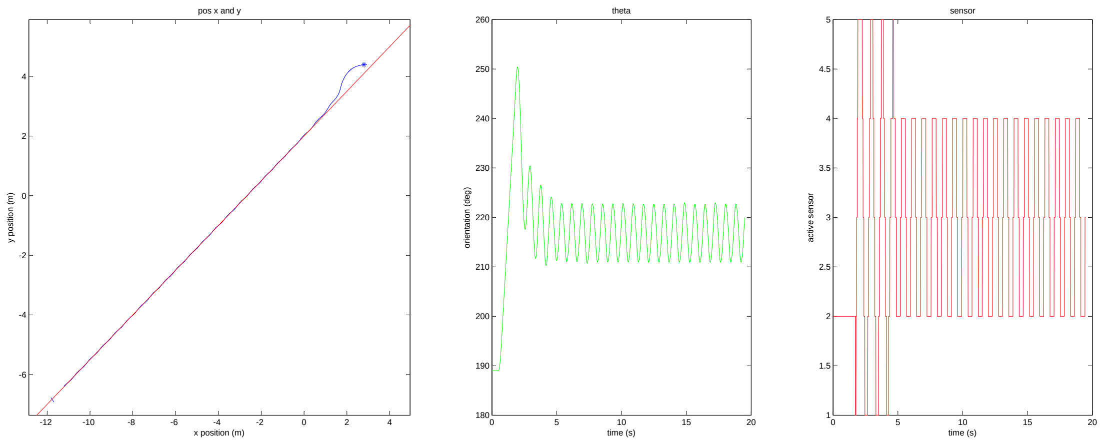


Figure 4.10: Simulated P Response on a Straight Line

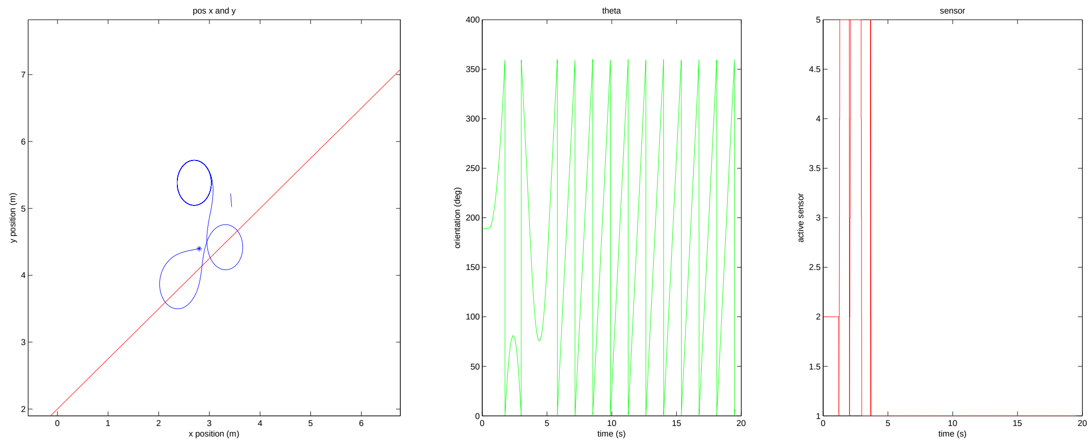


Figure 4.11: Simulated PI Response on a Straight Line

in the linear modelling, it was known the main goal to achieve with PID control was the minimisation of the amount of oscillation, which relates to overshoot and the Integral factor in our PID control. However the problem noted was that the moment a K_I (integral gain) of any value is brought into the model, stability of the system is lost.

Figure 4.11 shows after the startup of the controller the integral gain impacted the output variable too much, resulting in higher overshoot to such an extent that the AGC got stuck in a circular root away from the track.

The researcher suspected that this overshoot was as a result of the low resolution from the sensor feedback. The controller only knows of 5 possible positions and always aims to get it to 3. To further compare the P controller with the linear controller, movement along a curve was also modelled, as per Figure 4.12.

In this figure one can see that the line was tracked fairly well; however an oscillation was

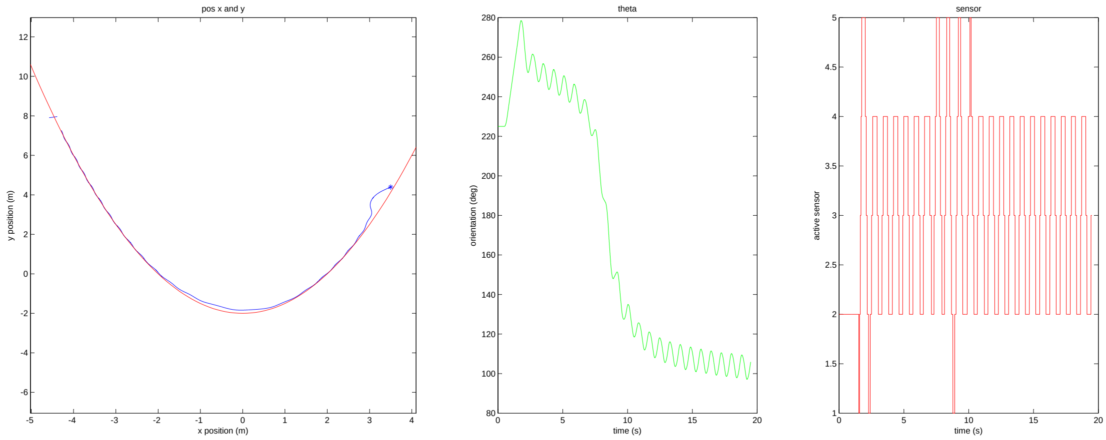


Figure 4.12: Simulated P Response on a Corner

seen in the turning which was not evident in the linear motion.

Low resolution

Chang *et al.* (2001) reported on motor control with a low resolution sensor. In their project, they refer to the monitoring of the position of the motor, and the low resolution refers to a sensor with a 3° resolution over a revolution. That resolution is far higher than in the subject research. They too modelled the system to estimate position and support control.

Azlan *et al.* (2007) worked on a simple line-following robot with two light sensors, which provided an analogue output, allowing for a higher resolution of position. They developed a fuzzy logic controller to run their robot. As part of their experiments they ran similar tests on the same robot having only the two sensors in an on/off format. To track the same route took twice as long with the lower resolution robot; its tracking was not as smooth and resulted in a high tendency to stray from the line.

4.1.2 PLC implementation

To test the components of the AGC and get an initial start point, the PLC was programmed to respond in a linear fashion to sensor input. Initial testing indicated that slight calibration was required to ensure that equal inputs for the motor controller resulted in equal outputs of the motor's speed. This was because of a combination of factors, the main two being the dissimilar input variables on the motor controller (132 bit control resulting in an uneven forward/backward ratio) and the difference in forward/reverse speeds of the motors (the motors being mounted asymmetrically).

Calibration was completed fairly easily by tabling maximum forward and reverse input values for the left and right motor and comparing the output speeds to ascertain the points where they share a maximum speed. Linear interpolation between the zero value and this value was then used.

One problem encountered with the PLC was that it specified all its data in bits or words (equal to two bytes). However, the motor controller required input data in the form of individual bytes. It was possible to send an individual byte from the PLC, but then only one motor could be controlled. Therefore it was necessary to combine the individual motor speed bytes into one word.

This was achieved by specifying the output byte equal to the first byte multiplied by 0x100 (using hexadecimal notation) and then adding the second byte.

For example if motor 1 were specified as decimal 40 (0x28) and motor 2 as 160 (0xA0) one could combine the two separate bytes into one word by defining

$$\text{Output} = (0\text{x}28 \times 0\text{x}100) + 0\text{x}A0 = 28A0 \tag{4.4}$$

Linear Response

The linear response method used recognises the five individual sensors, and, depending on which sensor is activated at any given time, has a preset table of values that correlate to motor speeds. When the centre sensor is active that AGC drives straight, if one of the two neighbouring sensors are active the AGC turns gradually in the opposite direction. Activating one of the outer sensors turns the AGC slightly faster in the opposite direction, always trying to return to the centre.

While this method of control is straightforward and reliable, the resulting movement is not ideal. This is largely as a result of the low resolution and the resulting overshoot which often occurs. The AGC generally takes multiple oscillations to recover from this overshoot. A good controller would reduce the speed at which it is turning as it nears the desired direction of travel, similar to some of the functions of a PID controller. To do this in a simpler fashion one could program different table values depending on which sensor was previously activated: however this is very difficult using only the FBD programming method.

That being said the control method was reliable: the AGC never left the track. Although the movement was not ideal and looked unstable (more noticeable at higher speeds), this did not affect its functionality.

PID

On a straight line the linear and P-controller models both had similar results, but on a curved route the linear model had better tracking. Although the results of implementing this control method into the PLC were successful the researcher still felt it necessary to test the implementation of the PID controller on the PLC. Much like in the model, a PID controller was setup for each of the motors. In this way we have two output variables that influence the process value.

A PID function block was set up in the TwidoSuite software used for programming the PLC. A variable was created which interpreted the discrete sensor values and gave a quasi-analogue value of the position of the AGC (as discussed in Section 4.1.1). Each sensor was assigned a value from 2 to 10, in multiples of two. For instance, if sensors 2 and 3 were active, their combined value would be ten, which if divided by the number of active sensors (two) would equal five. As such six would indicate the middle point of the sensor array. See Figure 4.5.

For the PID controller 6 was defined as the setpoint and the variable MV was given as the current equivalent analogue sensor value. The output for each was set to be between 0 and 63 (PV). These values were then manipulated so as to be valid for the motor controller. The resulting value is then the variable set in the serial transmission table as explained later in this chapter.

Testing with the PID controllers however resulted in extremely erratic behaviour. Alterations were made to the setup of the individual controllers and tuning; however no form of stability could be reached. Normally a a hard-coded PID controller is possible, but the limitation of FBD programming meant this could not be achieved for this application. As a result, control was reverted to the linear steering method.

The biggest difficulty of implementing the PID control on the PLC was in the form of feedback. It was relatively easy to set all the variables on the PLC to get the AGC to run. However without visual access to the changing variables on the PLC, it is difficult to analyse the resulting behaviour and to debug. This same problem arose when trying to quantify the visual movement of the AGC. One can see the response it made, but this cannot be measured easily in to improve on it.

These issues are not problems while modelling. One can see every variable at every step of the program and also have the exact values of the AGC's position and other state variables. This makes debugging and optimisation easy. Watching the AGC in operation, one can conclude, for example, that it is reacting too quickly and thus lower the proportional multiplier, but fine-tuning and understanding all the inputs is difficult.

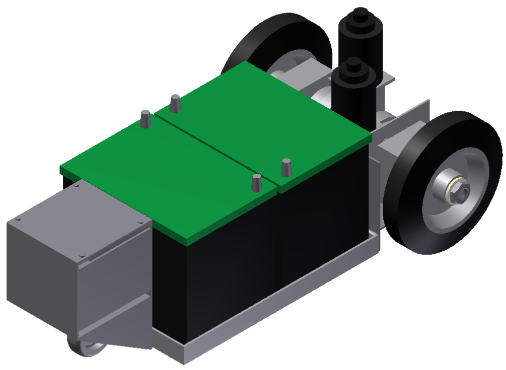


Figure 4.13: Final Prototype Design

4.2 Structure

Several modifications were made to the initial design in Section 3.4 to support the large number of components. The final design sent for manufacture is shown in Figure 4.13. Further modifications made to support additional components are listed in this section.

4.2.1 Wheels

Two types of wheels were required to complete the design. The two rear wheels would be of the same type, and would be the driving wheels; the single front wheel would need to be free to rotate and be able to support the rest of the weight of the AGC.

Most of the calculations for torque and drive speeds had been done assuming a wheel diameter of 200 mm. As such the researcher decided to source wheels of the same diameter as this would ensure the design would work without extra modifications. In addition, each wheel would have to be capable of supporting a minimum of 25 kg, but preferably more.

Wheels come in many different forms and materials. The researcher decided to choose a solid wheel design, rather than a tube that would require pumping up and be susceptible to punctures. Rubber wheels were selected in place of solid plastic or metal, as the properties of rubber would provide superior grip.

Suppliers' lists of wheels were analysed and a competitively priced rubber wheel manufactured by LAG was selected. The wheel (model 13136) is made up of a plastic frame with a solid rubber tyre section, shown in cross-section in Figure 4.14. The wheel has a width of 60 mm, can support 205 kg and comes prefitted with two bushes with an internal diameter of 20 mm.

The differential drive method of the AGC means it is sometimes possible for the front of the AGC to move sideways relative to the direction in which it is facing. This means that putting two wheels at the front of the AGC in a similar fashion to the driving wheels would lead to excessive wear on the tyres and extra resistance for the driving wheels.

The easiest solution was to use one or two wheels capable of rotating on the spot. A simple solution for this is a castor wheel. Castor wheels are commonly found in industry as they provide vehicles with easy mobility. No specific size was required, but smaller was assumed to be better as it would help retain the small size of the AGC. If one wheel were to be used it would have to be capable of supporting at least 25 kg. Once again several suppliers' lists of available wheels were perused and a suitable wheel chosen.

A Tente wheel (model number 2470PJO075P40PFP) was chosen. It has fixing plate dimensions of 60x60 mm, a load capacity of 75 kg, wheel dimensions of diameter 75 mm, width 25 mm and an overall height of 100 mm.

The original body design was a general design using projected components and estimated dimensions. Several sections of the design had to be updated with the finalisation of some components and actually obtaining them.

4.2.2 Motor Mounts and Bearings

DOGA 319 series motors have two sets of three M6 threaded holes that could be used for mounting the motors. A set of three holes matching the larger PCD mounting points was added to the two upright mounting plates. One side's hole placements were mirrored to match the opposite direction of the second motor.

Gears, bands and other forms of torque transmission have certain inherent problems. These can often be overcome to take advantage of the benefits that that they provide. Mainly an easy way to alter torque/speed ratios and also allow motors and wheels to be mounted dissimilarly. However, to keep the AGC physically small and minimise further transmission problems, the researcher decided early in the design phase that a direct drive method be used, thus negating the need for gears. This necessitated the need for motors that came equipped with the required power and speed characteristics. It was understood that the motors purchased would have pre-assembled gear boxes to provide the required power and speed characteristics, and no additional gearing was desired.

Figure 4.14: Cross-Section of LAG Driving Wheel LAG (2012)

The motors have a shaft diameter of 12 mm and a length of 25.5 mm minus the 3 mm used for the mounting plate. This length is only half the width of the driving wheels and the diameter is also considerably less than that of the wheel's internal diameter. As such some form of shaft or bush was required to transfer the torque from the motors to the wheels.

Design constraints determined that the motor's axle should not experience axial or radial forces greater than 50 N. It was expected that each wheel would have to support more than 180 N and bearings would be required to support the weight of the system from the wheels. Two bearings would be required for each transmission shaft to ensure the motor shafts did not experience unnecessary stress.

The researcher devised the following solution:

- A bearing block machined from aluminium to house two bearings.
- Two appropriate bearings housed in the bearing blocking to support a transmission shaft.

The design seen in Figure 4.15 was developed. The transmission shaft, machined out of mild steel, rests within the bearing block. One end is open to allow the motor's shaft to fit inside, and the other has space to support a wheel. The wheels have an internal diameter of 20 mm and the motor shaft a diameter of 8 mm. A shaft was designed with

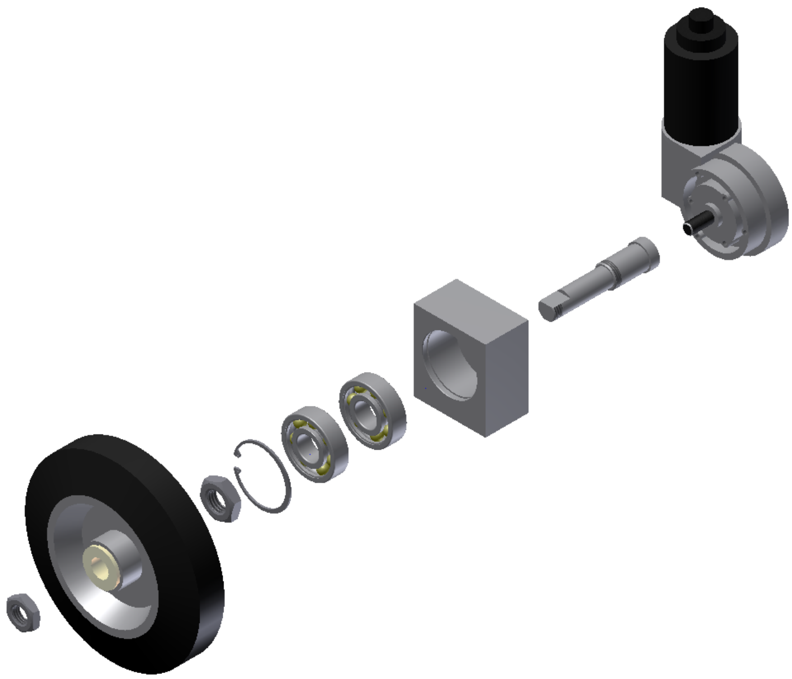


Figure 4.15: Model Displaying Wheel Support Design

these measurements in mind and adapted to support standard bearings that could fit in the allocated space.

The motor shaft comes prefabricated with a keyway, but because of the design of the shaft and the method used for cutting a keyway in a shaft, the researcher considered the use of a key infeasible. Instead a hole was drilled through the outermost ridge towards the centre of the shaft. It was then threaded and a grub screw was used to convey the torque from the motor to the shaft. The grub screw turns into the keyhole on the motor shaft. Although there is a slight gap, the resulting play is negligible.

The two bearings push up next to each other and against a ridge on the far side of the bearing block. They are further held in place by a press fit; to ensure no lateral movement an internal circlip is also used.

To prevent the shaft moving laterally, on the one side it has a lip which sits flush against one of the bearings, and on the other side a bolt screws onto the thread of the shaft and tightens against the other bearing.

The wheel is then placed on the shaft with another bolt to secure it. To prevent slipping, a hole is drilled radially through the wheel's inner section. A bolt is threaded into the wheel's plastic body and tightens against a flat that is machined onto the shaft. This ensures that the wheel turns with the shaft.

4.2.3 Buttons and Switches

A panel box was designed to fit at the front of the AGC to contain the large amount of electronics. The box provided space for the PLC to be mounted as well as several of the buttons and switches. It was located on top of the front castor wheel. A removable lid held down by bolts was used to enclose the electronics, and slots were left open at the top and bottom of the box on either side to allow for wires to pass through. A diagram of the box is shown in Figure 4.16.

When the box was manufactured specific components were not specified and no holes for mounting the components were allocated; these had to be drilled at a later stage. The model of the updated design (see Appendix D) contains these holes. Mounting holes for the following components were added:

- On the right hand side, four holes were drilled to mount the power switch and a fifth to allow the switch to sit inside.
- On the left hand side, two holes were drilled so a DIN rail for the PLC could be mounted. Two holes were drilled for the mounting of connector blocks on the inside of the box.

- On the back of the box two holes were drilled to mount the 24 V linear regulators and their appropriate heat sinks.
- On the lid two holes were drilled for the mounting of red and green push buttons. A third hole was drilled for the emergency stop button. An additional two holes were drilled for the mounting of the LED clips and two extra holes for each LED to allow the wires to pass through.

Figure 4.17 shows some of the additional components.

4.2.4 Sensors

To mount the array of induction sensors a perspex bracket was fabricated for the prototype. Because several different configurations were to be tested it was felt that this was the easiest method for the prototype. In later models this could also be manufactured from steel and form part of the frame.

Two holes were drilled on the bottom of the box at the front of the AGC to act as mounting points for the bracket. A sheet of 3 mm perspex was purchased and cut to size. A drill bit generally used for large diameter holes in wood was used to drill five holes with

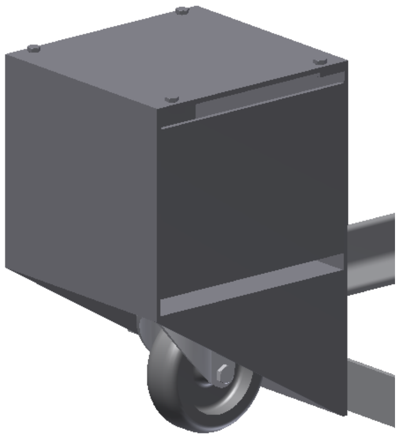


Figure 4.16: Box Located at Front of AGC Containing Electronics

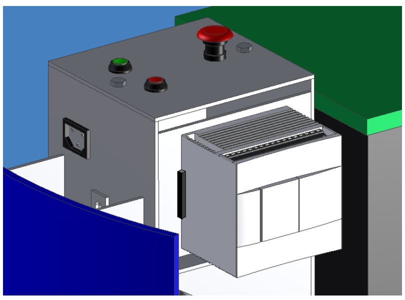


Figure 4.17: Box with Additional Components

centre points 5 cm apart to match the modelled system, for the placement of the induction sensors. Two bolts were used to mount the bracket in place. A photo of the prototype brace can be seen in Figure 4.18.

A second bracket was also made that placed the sensors closer together, in the hope that the smaller distance between sensors would lead to better control. However with the sensors so close to each other, interference occurred and often the sensors would react incorrectly to given inputs.

4.2.5 Bumper

As with several other components, the bumper module was added after the body was manufactured. It was required that the bumper be mounted at the front of the AGC and be capable of protecting the sensor array. For the prototype a makeshift mounting using perspex pieces was used, but the manufacturing drawings were updated to include a more permanent mounting.

The bumper consists of a large, slightly curved perspex sheet connected to the robot by two threaded M6 steel dowels. It is held in place by pairs of nuts allowing a small amount of movement. The two dowels are supported by perspex braces glued in place on the AGC and secured with more nuts, allowing slight lateral movement but preventing the bumper from falling out. A photo of the installed bumper can be seen in Figure 4.19.

4.2.6 Other

Mounting holes for the RFID reader and the motor controller also had to be drilled.

The RFID unit was mounted on the battery frame near the front of the AGC. A small piece of perspex was cut out to support the RFID reader. The reader was bolted to the perspex and the perspex was in turn bolted to the AGC's frame. A photo of the modification can be seen in Figure 4.20. For the prototype it was adequate to simply use a piece of perspex,

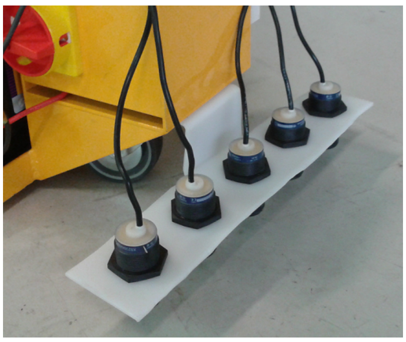


Figure 4.18: A Photo Showing the Mounted Bracket with Installed Sensors

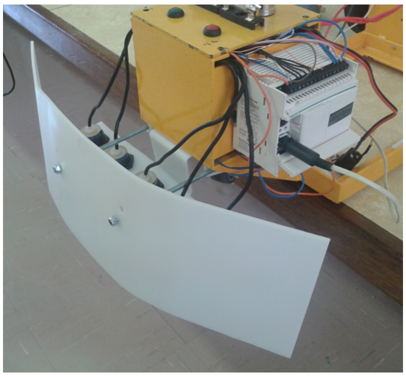


Figure 4.19: Photo of Installed Bumper on AGC

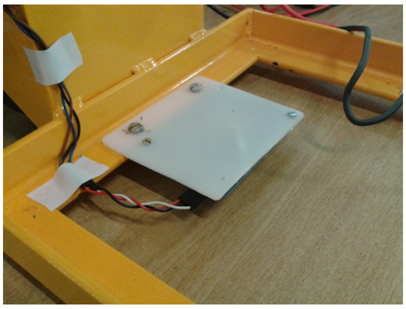


Figure 4.20: Photo Showing the Mounting of the RFID Unit

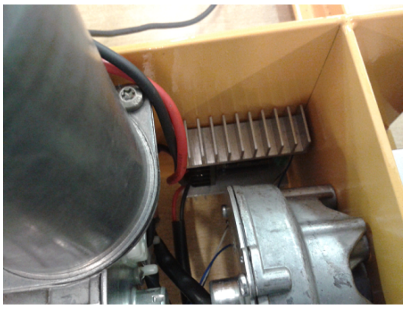


Figure 4.21: Photo Showing the Mounting of the Motor Controller

however for a production unit a steel casing has been designed and these modifications are indicated in Appendix D.

The motor controller was mounted at the back of the AGC between the motors. Four holes were drilled and the motor controller was mounted flush with one of the upright panels using the mounting points on the board. A photo of the installed motor controller can be seen in Figure 4.21.

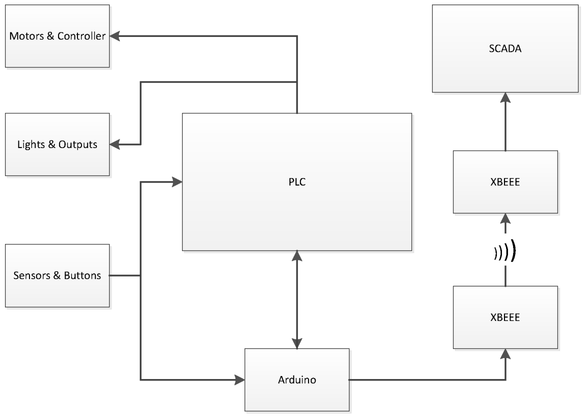


Figure 4.22: System Electronic Schematic

4.2.7 Manufacture

The manufacturing of the structure was undertaken by Frost Installations CC (Port Elizabeth) using a copy of the drawings generated for the production of the unit. Digital copies of all parts that were to be laser cut were also supplied in the form of DWG draughtsman's files.

Besides the battery mounting, which was made of angle steel, the rest of the body was made up of 3 mm mild steel sheet. These parts were all welded together.

The two bearing blocks were milled out of standard grade aluminium. The two shafts were lathed from mild steel rods.

To protect the mild steel parts from corrosion a coating was sprayed on the frame of the AGC and to the shafts were electro-plated; this work was performed by ID Control. After the shafts were electro-plated they were returned to Frost Installations so the surface that is in contact with the bearings could be re-polished for a better fit.

4.3 Electronics

A wiring-diagram of the system can be seen in Appendix C and as a schematic in Figure 4.22. The electronic supply for the circuit comprises two 12 V, 62 Ah lead-acid batteries as commonly used in automobiles. These batteries are connected in parallel to give a combined 24 V. From the battery terminal the ground wire splits to two points. One goes to the motor driver and the other is fed to the rest of the electronics via connector blocks. The line to the motor driver first goes through a normally open relay capable of handling high currents. This relay is switched by a normally closed emergency stop button; in the event of something going wrong, the emergency stop button can be pressed and power to the motors will cease.

The positive 24 V goes through a high-current power switch before splitting. A line is laid to the motor controller at the back of the AGC, while another line goes to a pair of 24 V DC linear voltage regulators to supply the electronics on board with a more stable supply. The voltage regulators (ON Semiconductor MC7824CT) are each capable of supplying 2 A. This power is then distributed via a set of connector blocks to the PLC and other electronics.

4.3.1 Lack of Serial Ports

As mentioned in Section 3.7.3, the PLC selected only had one available RS232 serial port. The project required at least two such ports. To solve this it was decided that only critical components would communicate directly with the PLC, in this case just the motor controller. The other devices, the RFID reader and wireless unit, did not need to be connected directly to the PLC.

The controller does not require the data from the RFID reader, it only requires confirmation that a valid set of data has been read. The researcher decided to use a small microcontroller to achieve this; an Arduino microcontroller was selected to get the setup running quickly as it does not require any extra circuitry or configuration to get it working.

The Arduino Uno microcontroller has one hardware defined serial port, although other digital I/O pins can be used for serial communication. Including the hardware defined serial I/O ports, the Arduino has 14 digital I/O pins and 6 analogue input pins. Five of the digital I/O pins can be put into pulse width modulation (PWM) mode to achieve analogue outputs. The board includes a FTDI chip that allows programming and serial communication from a computer via USB in the form of a virtual COM port.

Although more than one serial port is available, only one is actually needed as communication with the RFID unit is only one way. Data is received from the unit, but none is sent to it. The wireless unit is used only to transmit data to the SCADA system as the design doesn't require communication from the computer. Thus the Arduino's hardware RX line can be used to receive information from the RFID unit, and its TX line to send information to the XBee unit.

To allow extra data about the state of the AGC to be sent to the SCADA system, digital output pins on the PLC and digital input pins on the Arduino were connected. Two lines were connected. One specifies whether the AGC is moving or stopped and the other indicates if there is an error of some sort, for example activation of the emergency button. Similarly a digital output on the Arduino was connected (via a transistor) to one of the PLC's inputs so that the PLC can be notified when RFID data is received.

4.3.2 Further Serial Problems

Section 3.7.3 describes how a TDR232 module was selected to allow the PLC to communicate via RS232 serial connection with the motor controller. The module makes use of a specific mini-DIN 8 pin plug, cables for which are not readily available. As such a suitable cable was manufactured to specification (Figure 4.23a) and can be seen in Figure 4.23b.

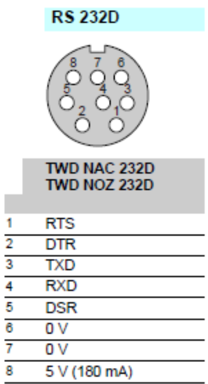
During testing however, serial data was not correctly transmitted over this connection. Extensive testing was performed with other serial devices and no solution to the problem could be found. Contact was made with Telemecanique support both in South Africa and overseas to try and solve the problem. The software was checked and tested by support staff who validated the code.

Hardware configurations were checked and no conclusion could be reached as to the cause of the problem. To get the system running the researcher decided to use the other serial port on the system, which uses the RS485 protocol and is used for programming. The programming cable (TSXPCX1031) contains a built in RS485 > RS232 converter. On testing the system with the computer the correct data was received. However the computer and programming cable operate at 10 V peak serial, whereas the controller uses a 5 V TTL (Transistor-Transistor Logic) signal.

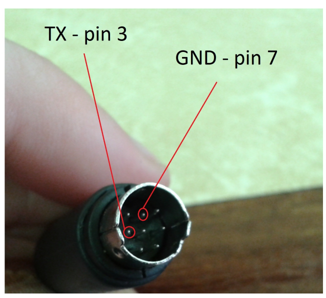
To convert the signals a MAX232 IC was used. Figure 4.24 shows the circuit diagram used to achieve the desired communication. The circuit was built onto a section of proto-board for testing purposes and integrated into the system.

Connecting the setup in this configuration enabled successful communication between the PLC and the motor controller and thus control of the motors was achieved.

At a later stage it was discovered that the same voltage difference between the PLC's RS485 output and that on the motor controller was the reason that communication between the RS232 module and the motor controller failed. Again, using the MAX232 IC, a stable



(a) RS232 Cable Wiring (Telemecanique, 2004)



(b) Picture Illustrating Connection

Figure 4.23: Custom RS232 Wiring and Picture

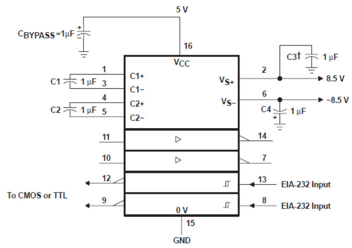


Figure 4.24: Suggested Max232 Circuit (Texas Instruments, 2004)

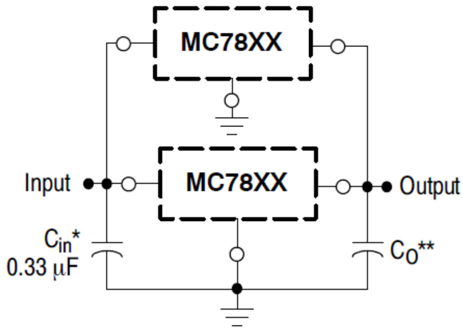


Figure 4.25: Wiring Diagram for Parallel 24 V regulators (ON Semiconductor, 2012)

connection was made between the RS232 module and the motor controller, leaving the RS485 port open for programming and debugging.

4.3.3 Voltage Regulators

Several voltage regulators were used by the system to ensure a stable supply for the various electronic devices.

24V Regulator

Two ON Semiconductor MC7824CT 24 V regulators were used to supply the PLC and other electronics with a more stable voltage supply. These were placed in parallel to increase power output and, as recommended in the regulator's datasheet, capacitors were included to smooth the output. Each regulator had thermal paste applied on the back and was then mounted on a small heat sink to help heat dissipation during times of high current draw. See Figure 4.25 for reference.

9V Regulator

A single 9 V linear voltage regulator was used to help supply the Arduino with power. Although the Arduino has a built-in 5 V regulator, it should not be supplied with voltages

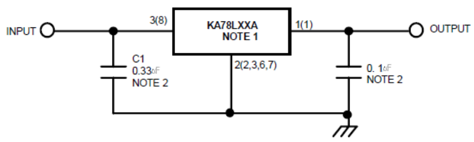


Figure 4.26: Wiring Diagram for 9 V regulator (Samsung Electronics, 1998)

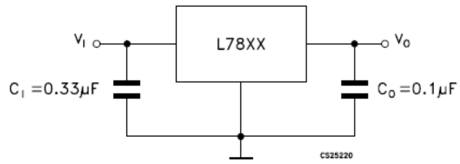


Figure 4.27: Wiring Diagram for 5 V Regulator (ST Microelectronics, 2010)

above 15 V. The large drop in voltage combined with a high current draw could cause the Arduino's small regulator to overheat.

While the Arduino itself has runs off 5 V, a 9 V regulator was used to provide power to the Arduino. The Arduino has a built in 5 V regulator, thus it is preferred to supply it with a higher voltage to avoid stability issues caused by a too low voltage.

The 9 V regulator (Samsung KA78L09A) had appropriate capacitors soldered in place as suggested in the data sheet. The circuit can be seen in Figure 4.26.

5V Regulator

Both the RFID unit and the XBee wireless unit required a 5V power supply. Although the Arduino includes a 5 V out line, it was felt that this element should be kept separate because the Arduino was not actually part of the original design. As such a 5 V linear voltage regulator (ST L7805CP) was selected to power these two devices.

Appropriate capacitors, as suggested in the regulator's data sheet, were added to the circuit. A circuit diagram for the section can be seen in Figure 4.27.

4.3.4 PLC

All the PLC's wire connections were made with simple screw terminals. A mini-DIN 8 pin plug was used for the programming cable and serial connection.

Besides the serial connections, the PLC has several others, including the power connection. It requires a 24 V DC supply, drawing a maximum of 200 mA. This is supplied directly from the voltage regulators, with two lines providing a positive 24 V and ground signal respectively (See Figure 4.25).

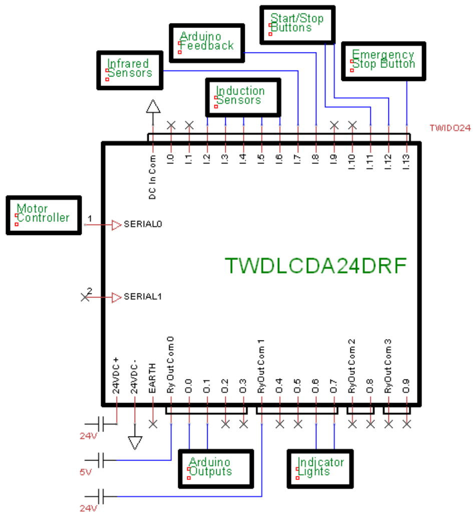


Figure 4.28: Wiring Diagram for the PLC

The signal lines from the various sensors and buttons are attached along the top of the PLC. All the sensors used were of the NPN transistor form. This means that their signal line pulls down to ground when activated. To ensure the PLC recognises these connections, the common input signal line is connected to ground. Each sensor is then assigned an input line to which its signal line is connected.

Buttons and sensors are also connected along the top row.

Next to the power supply lines on the bottom of the PLC are 10 relayed output switches. They are separated into four different sections and each section can be connected to a different common line. The pins are grouped four, four, two, two. The first four pins are connected to a common 5 V line and used to send information to the Arduino relating to the state of the PLC. The second four pins are connected to a common 24 V line and used to switch the lights on and off.

The wiring for the PLC can be seen in Figure 4.28.

4.3.5 Arduino, RFID and XBee

The Arduino and RFID and XBee modules all run off 5 V. The Arduino has a built in voltage regulator, but running it for long periods from 24 V is dangerous as the large voltage difference can cause the regulator to overheat. As such it is supplied with power from a 9 V voltage regulator.

Because the system was originally designed without the Arduino an extra 5 V regulator was used to supply the RFID and XBee. The Arduino uses only five of its pins (refer to Figure 4.29). D0 (RX) is used to receive serial information from the RIFD unit. D1 (TX) is used to transmit serial data to the XBee. D2 and D3 are digital input lines connected

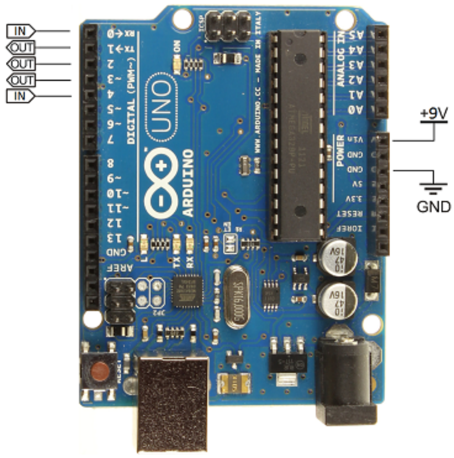


Figure 4.29: Wiring Diagram and Layout of Arduino Uno (Arduino, 2012)

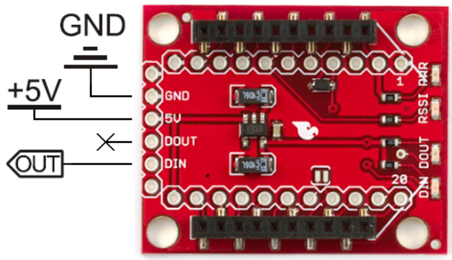


Figure 4.30: Pinout and Layout of XBee Xplorer Unit (Sparkfun, 2012)

to the PLC's outputs and are used to receive data from the PLC relating to its running state. D4 is a digital output connected to one of the PLC's inputs via a transistor. This is used to communicate with the PLC and notify it when an RFID marker is encountered.

The XBee unit itself has many inputs and outputs, as illustrated in Figure 4.30. The XBee explorer interface board however has just four lines, RX and TX for serial communication and VCC and GND. VCC and GND are connected to the 5 V line from the voltage regulator and the ground lines respectively. The RX line is connected to the Arduino's TX (D1) line. The TX line is not connected as it is not required.

The Parallax RFID unit also has four pins (refer to Figure 4.31). It has a VCC line and a GND line which are connected to the 5V voltage regulator and the system ground line respectively. It also has an !ENAB line which needs to be pulled low to enable the reader. In this case the pin is connected directly to the ground line on the RFID reader as it needs to be monitoring constantly for a marker. The last pin is the DATA or transmit line which is connected to the RX (D0) pin on the Arduino.

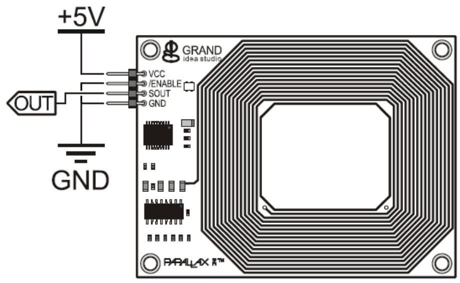


Figure 4.31: Wiring Diagram and Layout of Parallax RFID Unit (Parallax, 2010)

4.3.6 Motor Controller

The motor controller chosen was the Sabertooth 2x25 dual 25A unit. It would be controlled via a serial connection with the PLC and it is supplied with roughly 24 V DC directly from the batteries. In certain circumstances when the motors are in generator mode it is possible that the batteries will be charged by the motors being turned.

The controller has two sets of connectors, all of which operate via screw terminals. The power connectors are situated on one side of the controller, with the data connectors on the other. There are also a set of DIP switches used to set certain parameters of the controller and three status LEDs. See Figure 4.32 for reference.

The power connectors have a terminal for B+ and B which are connected to the +24 V from the battery and the negative battery terminal or common ground line. The left hand motor is connected to the terminal for motor 1, labelled M1A and M1B for the positive and negative motor terminals respectively. The right hand motor is connected to terminals M2A and M2B for the negative and positive motor terminals respectively, opposite to that of the first motor. This is because the second motor is mounted facing the opposite direction to the first motor.

The signal screw terminal has four points. The 5V point is a 5 V regulated output for use with remote control wireless receivers. S1 and S2 are for receiving motor commands.

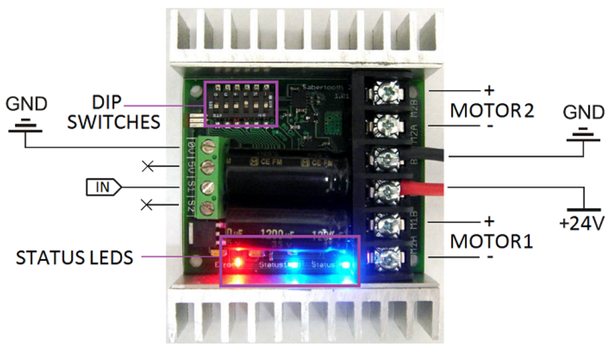


Figure 4.32: Wiring Diagram for Sabretooth 2x25 Motor Controller (Dimension Engineering, 2007)

Table 4.1: Sabretooth DIP Switches

Switch	State	Defined
1	ON	Control Mode
2	OFF	Control Mode
3	OFF	Lithium cut-off
4	ON	Baud Rate
5	ON	Baud Rate
6	ON	Serial with/out Slave Select

For serial only S1 is used. S1 is the controller's RX line. It and the 0 V (ground) line are connected to the PLC via the PLC's serial connector.

The DIP switches are used to set several parameters of the controller, including the type of input to be used and the speed of the serial connection (if a serial connection is being used), as well as activate extra protection for li-ion batteries. An explanation of the switches can be seen in Table 4.1

The Sabertooth has three status LEDs. The red error LED illuminates if a fault occurs. Potential errors include a flat battery, over-heating, over-current or over-voltage. The blue Status1 LED illuminates when the controller has power and is in a state of readiness. The blue Status2 LED is not used in the current setup of the controller.

4.3.7 Sensors, Buttons and Lights

Several sensors, buttons, switches and lights complete the AGC's circuitry. Five induction sensors (Telemecanique XS230AANAL2) are used to monitor the AGC's position relative to the track it follows. These sensors are simple proxy sensors with a fixed measurement distance.

The sensors require 12 - 48 VDC to work. The sensors have three wires: black, blue and brown. Brown is connected to the regulated 24 V DC, blue to ground and the black line is the signal line, connected to the PLC. The sensors are of the NPN current sinking variety and are normally open (NO). As such, when activated, their signal line pulls the PLC's input line down. See Figure 4.33 for reference.

4.3.8 Bumper

The bumper installed at the front of the AGC serves a double function. It was designed to protect the AGC as well as to act as an emergency stop button should an obstruction be encountered. The bumper is supported by two threaded steel-dowels that are able to move backwards and forwards slightly. Two reed switches were mounted on the AGC with corresponding magnets on the steel dowels. If the bumper is depressed the steel dowel

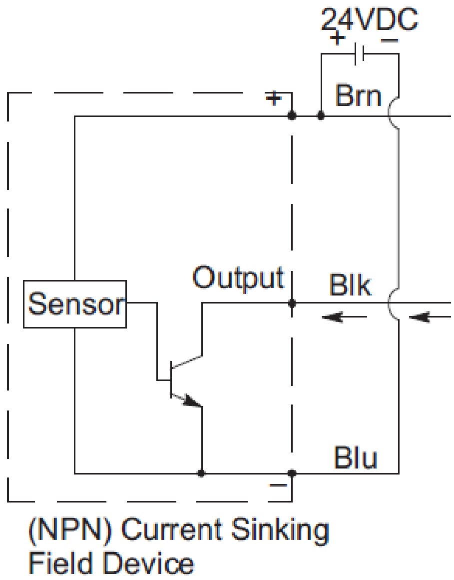


Figure 4.33: Wiring Diagram for an NPN Sensor (Stenerson, 2004)

moves backwards and the magnets activate the reed switches.

When triggered the reed switches activate one of the inputs on the PLC. To achieve this, the reed switch is connected between a 24 V point and an input pin on the PLC. The reed switches are capable of handling currents up to 0.5 A, whereas the PLC only sinks around 7 mA; thus no resistor was required to drop the current.

When activated the PLC acts in the same way as when the emergency button is pressed: the AGC is stopped immediately and the bumper must be reset before the AGC can be restarted.

4.3.9 Remote

During testing it was found that having to bend down continually to operate the buttons on the AGC could result in slight discomfort. To obviate this, a remote control receiver unit was installed in the AGC. This would also double as a safety feature, because someone does not necessarily need to be near the unit to stop it.

The remote has three buttons. The receiver unit was installed such that the three buttons act in the same fashion as those on the AGC itself, that is one button to start the AGC, one to stop it and one to act as a remote emergency stop.

For the emergency stop the latch function was used, requiring the remote emergency button to be pressed a second time before the AGC could continue. Each person responsible for loading and offloading the trolleys from the AGC can be given a remote.

The remote used in the prototype was of the same type used by automatic garage door and gate openers; it operated on a 24 V DC supply.

4.3.10 Emergency Stop

As has been discussed, the emergency stop button on the AGC, the bumper and the remote control all activate the software emergency stop on the PLC. However it is possible that a problem with the motor controller occurs and as a result commands from the PLC are ignored by the motor controller. In such a situation a hardware stop must be put in action.

A high-current relay (Panasonic CB1aH-24V) has been used to control power to the motor controller. From the main power switch the line goes via this relay to the motor controller. When the relay is activated the connection is made and power is supplied to the motor controller; when the switching circuit loses power, power is cut to the motor controller. To achieve this, a second switch (that is normally closed) was attached to the emergency stop button on the AGC and placed in series with one of the bumper switches that was set up to be normally closed.

Thus under normal circumstances current flows through the emergency stop button and the one reed switch on the bumper, activating the relay and providing power to the motor controller. When either of these devices is activated, power is cut to the relay, and in turn to the motor controller. During this time the PLC will still be powered and appropriate action can be taken.

Thus both a hardware and software emergency stop has been implemented.

4.3.11 Charger

The AGC is powered by two 12 V lead-acid batteries. To charge them the researcher decided to use two individual 12 V chargers as opposed to one 24 V, charging the batteries in parallel. While both methods are feasible, the batteries can become unbalanced after repeated charges, one being at a lower voltage than the other. This can damage the batteries and lead to a reduced life span.

GMSA specified full recharging of flat batteries overnight. A shift is roughly eight hours long which, allowing some time for movement, gives at least fourteen hours in which the batteries can be charged continuously. The battery is rated at 62 Ah of charge which gives:

$$\begin{aligned} I &= W/t \qquad (4.5) \\ &= 62 \text{ Ah}/14 \text{ h} \\ &= 4.43 \text{ A} \end{aligned}$$

Assuming a completely flat battery and a charger capable of charging at a fixed rate throughout the charge cycle (generally current drops the closer to full voltage the battery is) one would need a charger capable of supplying 4.43 A.

Ideally it would be best to use intelligent chargers. These chargers monitor battery conditions and voltages and provide charging capabilities more effectively extend battery life. However, they are also much more expensive: a low power (2 A) intelligent charger costs over R 500 and one supplying 5 A starting at R 1 200 (Midas, 2012).

It is difficult to estimate the extended cost benefit from using these chargers. Normal (non-intelligent) battery chargers simply apply a set voltage to the terminals and the battery is charged as fast as the capacity of the charger permits. When fully charged, it may switch to a trickle-charging state. It was possible to obtain a normal 7 A charger for only R 380.

Two 12 V car battery chargers capable of supplying in excess of 5 A were purchased . To avoid waste of time at the end of every shift where an operator had to disconnect the batteries from the AGC and then connect the chargers, and the possibility of human error that could result in severe battery damage, the researcher decided to install wiring to allow the chargers to be plugged into the AGC and charging to start automatically.

The wiring represented in Figure 4.34 was used.

This method of connecting can lead to trouble, as a short is created when the positive of one charger is connected to the negative of the other. However, these specific chargers are designed such that the outputs are isolated from the inputs. The researcher used a multi-meter to check if any continuity existed between the outputs on the two chargers and found none.

The two chargers were then wired up to use a common AC power, and their output was connected to a 3 prong plug. On the AGC a connecting socket was used which was connected to the two batteries.

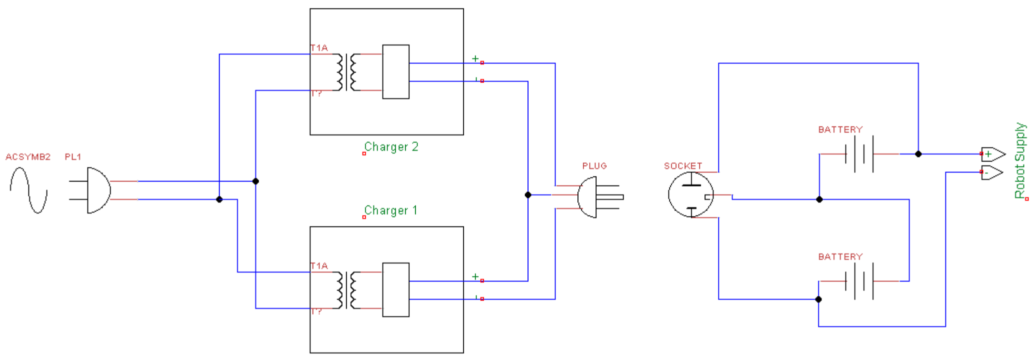


Figure 4.34: Wiring Diagram of Battery Chargers

4.4 Software

Three sets of code written for this project. The most important is the control software which runs on the PLC, which is the controlling software for the AGC. It monitors several input pins from different sensors and responds appropriately based on preprogrammed variables, switching several outputs in response.

The second program runs on an Arduino microcontroller. If a PLC with slightly better specifications were used, the Arduino's function in this project could be incorporated into the PLC. However for this project the Arduino was required to monitor the RFID reader and transfer this data to the wireless system as well as inform the PLC of the presence of a valid RFID tag. The third set of code manages the SCADA interface. It is comprised of two programs, one that monitors the wireless module for information from the AGC and stores it in a database, and a second that accesses the database and displays the information in a readable format.

4.4.1 PLC

The control software for the PLC was written and compiled using TwidoSuite v2.31.04, the officially supported software for programming Twido controllers by Schneider Electronics (which also trades under the name Telemecanique). The software allows one to program in one of two ways, using either standard ladder programming (FBD), or the compatible list programming. Any section of code can be displayed in either format; list programming is just a written version of the semi-graphical ladder programming.

The researcher originally thought that STL (structured text language), a common programming language used with PLCs, would be supported, but unfortunately the PLC did not support any programming languages other than those discussed above. This increased the difficulty of programming certain aspects of the project, and possibly limited it in certain areas.

The first step when programming the PLC was to set up the correct description of the system. The Twido systems are of a modular design and a drag drop interface was used to form a graphical representation of the system. The Twido TWDLCAA24DRF was selected as the main unit to which a TWDNAC232S Serial Adaptor was added. In addition, a generic ASCII Network Element was added to represent the motor driver.

The basic settings of the serial connection used were: baud rate (set to a low 2 400 bps to ensure minimum communications errors); parity (no); and number of data bits (8). In the advanced settings the defaults make use of a start and end character in every transmission.

Serial transmission from the Twido operates by setting up a transmission table. This table contains the data one wants to send as well as extra space for receiving data. The

	Most significant byte	Least significant byte
Control table	Command	Length (transmission/reception)
	Reserved (0)	Reserved (0)
Transmission table	Transmitted Byte 1	Transmitted Byte 2
	...	...
		Transmitted Byte n
	Transmitted Byte n+1	
Reception table	Received Byte 1	Received Byte 2
	...	...
		Received Byte p
	Received Byte p+1	

Control table

The **Length** byte contains the length of the transmission table in bytes (250 max.), which is overwritten by the number of characters received at the end of the reception, if reception is requested.

The **Command** byte must contain one of the following:

- 0: Transmission only
- 1: Send/receive
- 2: Reception Only

Figure 4.35: Transmission and Reception Table for Twido (Schneider Electric, 2009)

table also contains a byte which indicates whether the system should be set up for transmission, reception or both, and how many bytes are to be transmitted. An example of a transmission table can be seen in Figure 4.35 from the Twido's programming guide.

When set up in a "transmit only" mode, such as in this project, the system starts transmission, sends the data in the transmission table and then ends transmission. The process is then restarted. The motor controller cannot be programmed to ignore certain characters and assumes every value it receives to be a speed command. For this reason start and end characters must be removed from the setup.

To achieve this, the researcher disabled the start and end characters in the serial definition, but the software requires a definition on when to cease communication. As such the connection is defined to stop on the reception of 100 bytes, a situation that will never arise. Thus the only data that will be transmitted is limited to that found in the transmission table.

The program on the PLC was split into six sections: Section

1. Runs at the startup of the PLC and resets several variables;
2. Deals with the serial transmission. Serial data is sent to the motor controller to specify the speed of the independent motors. This section sets up the serial connection as earlier specified and is also responsible for the continuous sending of serial data;
3. Relates to the sensors and the setting of the correct motor speeds (see Section 4.1 on how this data affects the output);
4. Monitors the button inputs and respond appropriately;

5. Covers some of the peculiar situations that may arise, for example should the AGC lose the track. It also includes the timers for starting and the flashing of the lights; and

6. Contains the interaction with the Arduino, but only the outputs to the Arduino. The communication from the Arduino is viewed as a button press and is included in the appropriate section.

Basic Running

The PLC runs as follows: whenever the PLC starts up it is immediately and automatically put into stop mode. At any point when the green button is pushed, the controller ensures that the emergency button is not depressed, waits 2.5 s while flashing the green light and then puts the AGC into run mode.

If one of the AGC's sensors is activated, normal control will commence. If no route is immediately present, the AGC will proceed for 2.5 s in a straight line in an attempt to locate the route, and if this fails the AGC will stop. This will be controlled in the same way as when the red button is pushed. When this button is pushed the AGC's motors will stop, the red light will turn on and the green light will turn off. Depending on the AGC's speed before it receives a stop command, the AGC's momentum may result in it continuing to move for up to 20 cm.

If the AGC loses its track while running it will continue for 2.5 s at the same drive rate. If it finds the route within this time it will continue as normal, but if the track cannot be found it will stop and await further input.

When a valid marker is located by the RFID reader, the data on the marker is sent to the Arduino unit which then notifies the PLC. The PLC recognises this as a stop command and responds accordingly.

When the emergency button is pressed the AGC stops, the red light will start to flash and the Arduino is notified of this. This is the same response as when then bumper switches are activated. The AGC will not be able to proceed until the emergency button is reset.

If the IR proximity sensors detect an obstruction, the AGC is halted and will not move until the sensors acknowledge that the obstruction is no longer present. At this point the AGC will proceed without any required input from an operator.

At any time while the PLC is powered, pushing the red or emergency stop buttons, or activating the bumper switch, will immediately bring the AGC to a stop. At any stage (excluding when an emergency stop is active) when the green button is pushed, the AGC will proceed after 2.5 s.

Table 4.2: Data String Specification

String composition	--XXX--E--YYYYYYYYYY
XXX	3 Byte AGC ID Number
E	Single Byte Error Code
YYYYYYYYYY	10 Byte RFID marker code On interval transmission, all bytes are 0 besides last which indicates state

4.4.2 RFID

The initial design allowed for the connection of the RFID unit directly into the PLC. The PLC would monitor this input and send the required output on to the XBee unit which is used to communicate wirelessly with the SCADA system.

However, when the PLC was purchased it was noted that the desired setup would not be possible because of the limited extendibility of the system. Therefore as discussed above an Arduino microcontroller was obtained to monitor the input from the RFID reader. On receiving valid data from the RFID unit, the Arduino forwards this information to the SCADA system via the XBee unit with which it communicates.

The Arduino also monitors outputs from the PLC which indicate the state of the AGC, including power, running and error. Three bytes are also transmitted which identify which AGC is transmitting. These three bytes are hard-coded into the software, and should be different where multiple AGCs are in use. When a valid RFID tag is read, the Arduino also switches a digital input on the PLC. This bit is used to indicate to the AGC control that it has reached a marker and must stop.

Data is sent via the wireless setup every time an AGC crosses an RFID tag. In addition a timer ensures that the same data (excluding the RFID tag) is sent to the SCADA system every thirty seconds. This means one can keep track of the system from the SCADA interface and note any problems that occur. The string of data that is sent is shown in Table 4.2.

Arduino

The code operates in the following manner. Initially a setup function is called. This function starts the serial communication on the RX and TX pins of the Arduino. It is set up for communication at 2 400 bps which is the rate specified by the RFID unit (Parallax, 2010). In this instance the RX receives data from the RFID unit and the TX transmits to the XBee. As such the XBee was also set up to operate at 2 400 bps.

Pins 2, 3 and 4 are initialised as required as inputs and outputs. From there the main loop function is run. The loop constantly checks to see if there is available data in the

Start Byte (0x0A)	Unique ID Digit 1	Unique ID Digit 2	Unique ID Digit 3	Unique ID Digit 4	Unique ID Digit 5	Unique ID Digit 6	Unique ID Digit 7	Unique ID Digit 8	Unique ID Digit 9	Unique ID Digit 10	Stop Byte (0x0D)

The start byte and stop byte are used to easily identify that a correct string has been received from the reader (they correspond to line feed and carriage return characters, respectively). The middle ten bytes are the actual tag's unique ID. For example, for a tag with a valid ID of 0F0184F07A, the following bytes would be sent: 0x0A, 0x30, 0x46, 0x30, 0x31, 0x38, 0x34, 0x46, 0x30, 0x37, 0x41, 0x0D.

Figure 4.36: String from RFID Unit (Parallax, 2010)

Table 4.3: Parallax RFID Pin out

pin #	function
1	Power 5V VCC
2	Not Enable
3	Serial Out
4	GRND

serial buffer. If there is it reads the initial byte and checks if it is a 0x0A as specified by the RFID string transmission, which can be seen in Figure 4.36. If this is the case, it runs a function which sends the AGC's ID number and error state to the XBee unit. It then continues to loop and send the data it receives on RX directly to the XBee unit until an 0x0D value is read, indicating the end of the data from the RFID unit.

The unit is programmed to ignore data received for the next second, as a form of debounce and to prevent transmissions of unnecessary data to the SCADA system.

A timer, which runs concurrently with the above process, keeps track of how much time has elapsed since the last transmission. If this value is above 20 seconds a standard transmission takes place which sends out the AGC's ID number along with the error state and the general running state of the AGC.

Parallax RFID Unit

The Parallax RFID unit comprises a circuit board with built in antennae, indicator LED and 4 pin control. The pins are specified as can be seen in Table 4.3. The unit draws 20 mA of current when active and the unit is kept active by pulling pin 2 down. The indicator LED is green when inactive and red when active.

When a valid RFID tag is detected, the data is read from the tag and transmitted on the SOut pin. The unit uses standard 5 V TTL serial with a fixed transmission speed of 2 400 bps, 8 data bits, 1 stop bit and LSB (least significant bit) first.

Table 4.4: XBee Wireless Unit Pinout

pin #	function
1	Power 5V VCC
2	Serial In
3	Serial Out
4	GRND

XBee Wireless Unit

The XBee wireless unit is capable of transmission and reception of serial, analogue and digital signals from a matching unit. This project used XBee Series 1, non-Pro units shipped with wire antennae. The non-Pro units are capable of transmission of over 100 m line of sight, and 30 - 40 m through walls.

Although capable of various forms of data transmission, for the purposes of this project only the serial communication was used. The XBee units normally operate at 3.3 V, both for supply and signal. For easier integration into the system an XBee Xplorer unit was purchased which brought the operating voltage up to 5 V and provided four easily accessible pins for power and serial communication.

The XBee unit comes standard set up for 9 600 bps transmission. It is necessary to communicate with it via the Digi X-CTU software, downloadable free from Digi's website. The software allows one to view and alter all the internal settings of the XBee. To do this one needs a serial connection between the computer and the XBee.

For this an XBee USB Explorer was used. The USB explorer, much like the standard Xplorer, switches the operating voltage of the XBee to 5 V, the same as a computer's USB port. The unit also includes an FTDI chip which acts as a virtual serial port for the computer. This virtual COM port is then specified in the X-CTU software, and allows one to communicate with the XBee. The software also includes a serial monitor, a range test and several other functions for testing XBee units.

By selecting the appropriate baud rate and serial port from the list one can test for a valid Xbee unit. Clicking over to *Modem Configuration* allows one to specify the requested baud rate. The baud rate selected is 2 400 bps, to match up with the fixed baud rate of the RFID unit. This need only be done once.

4.4.3 SCADA

A server computer is needed to run the SCADA software, which is made up of several components. All the data received by the SCADA software is stored in a database, in this instance a MySQL database, but there are many different database types both commercial and free with which it could be interfaced.

Figure 4.37: Screenshot of SCADA Homepage

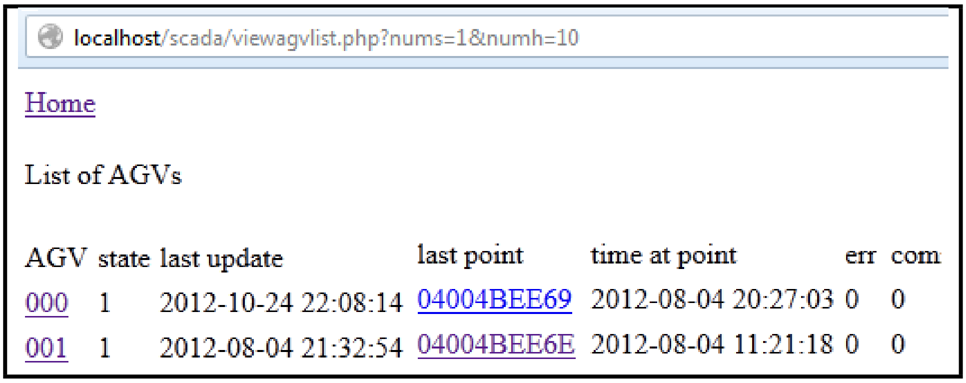


Figure 4.38: Screenshot of SCADA AGC List

Instructions for setting up the SCADA system on a computer can be found in Appendix E.

The server needs to run a Python program continuously. This program monitors the wireless XBee unit for incoming data. As data is received it records this data in the MySQL database. To view the information from this database a web-interface was developed making use of PHP, requiring a local webserver to process PHP and HTML commands. In this instance WAMP was installed on the server computer which is capable of processing the PHP and HTML as well as running the MySQL server.

A representation of the web interface is shown in Figure 4.37. The main page of interest, illustrated in Figure 4.38, gives a list of all the AGCs that have communicated with the system. For each AGC it lists the last checkpoint it crossed, the time of crossing, any errors and the last time data was received from a specific AGC.

It is also possible to view each AGC individually, as can be seen in Figure 4.39. By clicking on one of the AGCs, a log is displayed of the ten most recent communications. This can also be done for the checkpoints (Figure 4.40). By clicking on a checkpoint, a log of the last ten times an AGC crossed that checkpoint is displayed. A list of all the points is also available which indicates the last time an AGC travelled past it, as illustrated in Figure 4.41. One can also view a straight log of all AGC data (Figure 4.42).

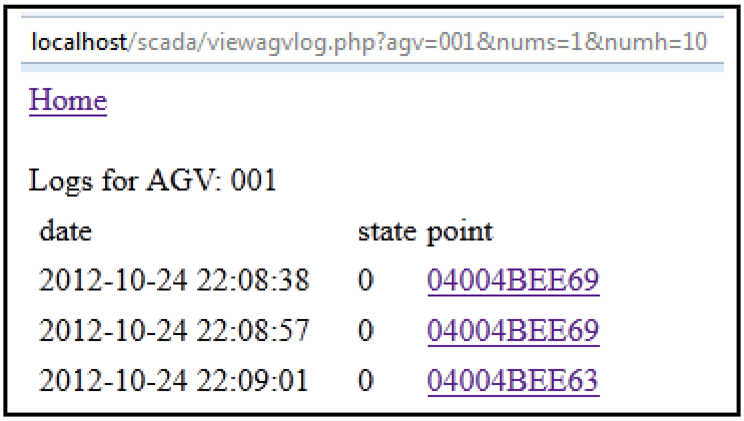


Figure 4.39: Screenshot of SCADA Individual AGC View

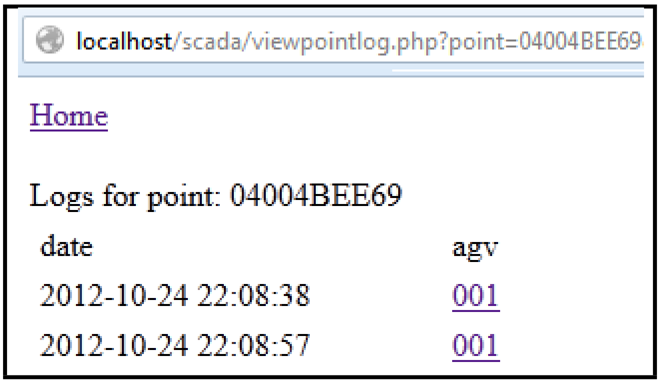


Figure 4.40: Screenshot of SCADA individual point view

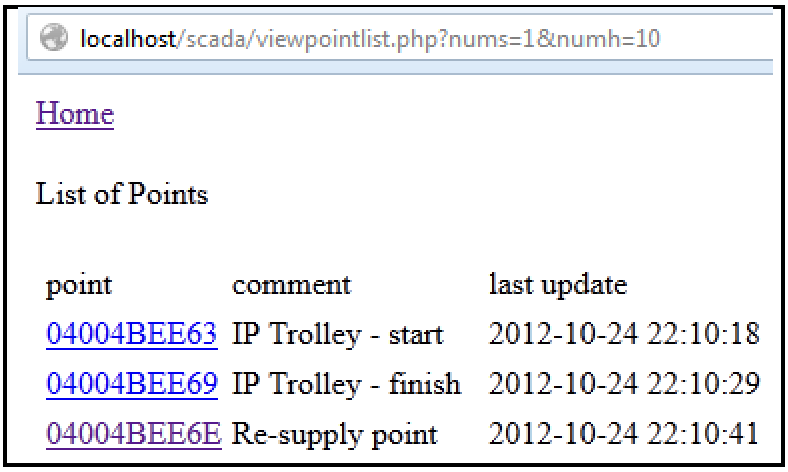
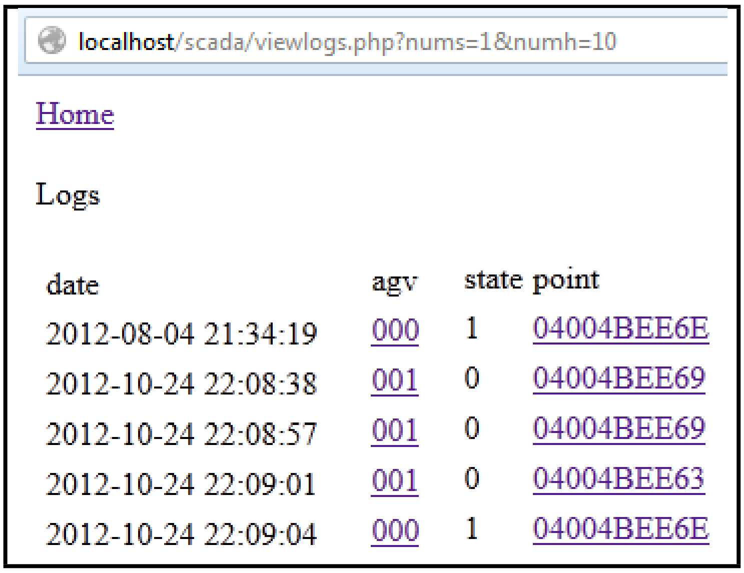


Figure 4.41: Screenshot of SCADA Points List



localhost/scada/viewlogs.php?nums=1&numh=10

Home

Logs

date	agv	state	point
2012-08-04 21:34:19	000	1	04004BEE6E
2012-10-24 22:08:38	001	0	04004BEE69
2012-10-24 22:08:57	001	0	04004BEE69
2012-10-24 22:09:01	001	0	04004BEE63
2012-10-24 22:09:04	000	1	04004BEE6E

Figure 4.42: Screenshot of SCADA Log

Python

The section of code that interfaces the wirelessly transmitted data from various AGCs to the database is written in Python. Python is a very popular programming language with a good user base and support structure. Serial communication from a computer can be difficult; one of the main reasons for using Python to solve this problem was the researcher's previous experience in using Python for implementing serial communication.

Although Python 3.3.0 is the latest version of Python, Python 2.7.3 was used. This was because the library written to deal with serial communication was initially written for Python 2 and thus most of the support for the libraries is focused on Python 2. Python 2.7.3 is the latest version of Python 2 to be released and still features support by the Python organisation. The 32-bit version of the software had to be used, as one of the libraries required is only compatible with this version.

Another benefit of Python is that it is free and multi-platform. Many Linux distributions as well as the OS X for Mac computers come with it pre-installed. The install is also freely available to download for any version of Windows since and including Windows XP.

There are two main parts to this program, first the interaction with the XBee wireless module via serial communication and second the storage of this data in a MySQL database. For both of these features appropriate libraries were used.

For the serial monitoring, the *pyserial* 2.6 library (Liechti, 2010) was used. This library allows easy reading and writing to an installed COM port on the computer. This is manually specified in the source code and may need to be updated as the software is installed on different computers. The port is specified at the beginning of the program where the serial connection *ser* is declared. For Windows computers this is specified in the form of *COMX*, where X is the number of the relevant software defined port. This number can be confirmed by accessing the *Ports* list in *Device Manager*.

For the MySQL interaction, the MySQL-python 1.2.3 library (Dustman, 2010) was used. This library makes accessing and storing data in a MySQL database easier. When the database connection is created near the start of the program, several details are required:

- The address of the MySQL server;
- A MySQL username that has access to the database;
- The password for this username; and
- The name of the database to be accessed.

After instantiation, an infinite loop is run. In this loop the software continuously monitors for an expected pattern, which is indicative of a correct AGC log transmission. If the data is accepted as correct, the appropriate *update* and *insert* queries are run on the database which stores the new data in the MySQL database where it can be accessed by other programs.

PHP

To facilitate accessing the logs, and create the human interface for the SCADA system, PHP was used to code a web-interface. In conjunction with the appropriate HTML code, PHP allows one to process commands to access various databases.

Each view for the SCADA interface relates to a separate webpage. The first PHP command for each page is a command to connect to the MySQL database. The command is of the same format as in the Python code and includes the database address and login details.

SQL queries appropriate to the page are then run to display the required data. GET info, stored by appending *'?<variable>=<value>'* to the end of webpage addresses is used to carry data relating to which AGC or which point's data is supposed to be displayed.

Also included are which values to display from the log. By default this will be the ten most recent results and should less than ten results be available, only those are displayed. If more than ten are available, pertinent buttons are displayed allowing one to scroll through previous inserts.

A list of the pages and the relevant data displayed can be seen in Table 4.5.

WAMP

WAMP is a software package which allows one to run a webserver on any Windows computer. Alternatives for other operating systems also exist, such as LAMP for Linux.

Table 4.5: List of PHP Pages

filename	Description
index.php	Home page, shows list of options
viewagvlist.php	Page displays the list of all AGCs in the system
viewagvlog.php	Page displays log of a specific AGC
viewlogs.php	Page displays log of all recent AGC communications
viewpointlist.php	Page displays the list of all points in the system
viewpointlog.php	Page displays the log of a specific point

WAMP stands for Windows Apache MySQL PHP, the services which the package offers. Apache is used to serve HTML websites to browsers on request. This is needed to access the web interface. MySQL is used as the database in which to store logs, and PHP is used to run commands and access the MySQL database from the browser.

WAMP, and the software released under it, are all free applications. The WAMP package needs to be installed on the computer that is being run as the server. A Windows installer is available (Bourdon, 2012) which can be downloaded and will automatically start and set up the program.

The PHP pages need to be placed in the *www* folder of the WAMP install. This is to make them accessible from the browser. The appropriate database also needs to be created as well as a user which has access to this database. The easiest method to achieve this is to go to *localhost* from a browser, browse to *PHPmyadmin* and import the pre-created and empty database.

To check if it has been installed correctly, the browser must be used to go to *localhost*; then click on the subfolder relating to the SCADA interface and select one of the menu options.

XBee

The XBee wireless unit is used to communicate between the computer and the AGC. A pair of these units is used. The one plugged into the computer requires an extra device to allow it to operate at a higher voltage and communicate with the computer.

For this, an XBee USB Explorer was used, as mentioned in Section 4.4.2. The unit contains an FTDI chip to create a virtual serial port on the computer and a regulator to achieve correct voltage levels. It was initially needed to set up both XBee units for 2 400 bps communication correctly. After the initial setup it is used purely to create the link between the XBee and the computer.

Server Specifications

The setup requires a computer to run three main elements: the Python software that receives the AGC data and stores it in the MySQL database; the MySQL database that stores the information; and the Apache/PHP server which serves and interprets the web interface. These three services can be run on the same computer, or if desired to fit in with existing infrastructure, on separate servers.

The web-interface can be accessed from any computer linked to the same network and can be accessed from multiple computers or mobile devices without requiring any software installation.

Although none of the software packages specify minimum system requirements, the software exhibit no problems when run on any computer sold in the last 10 years. The software is not particularly resource intensive and a standard desktop computer or laptop can be used for the purpose. If more than 20 AGCs are to be used with a single server, and if constant supervision of this system is required, minimum specifications for the server may need to be developed to ensure stability.

A USB 2.0 port is required to interact with the XBee wireless unit, and if remote access is required a NIC (Network Interface Controller), for example an Ethernet or wireless port would be necessary.

4.5 Expected Performance

From the design perspective, the AGC should attain all of the required objectives:

- Motors were selected capable of accelerating and maintaining the AGC at the desired speed;
- Sensors were selected that would enable the AGC to follow a pre-laid metal strip;
- Safety components were included in the design from the outset;
- Software was developed capable of processing these signals and steering the AGC appropriately;
- Batteries were selected with sufficient capacity for the AGC to run continuously for an entire shift;
- Chargers were selected which had the capability of recharging these batteries between shifts; and
- A SCADA system was implemented whereby a computer could be used to monitor multiple AGCs on different routes or tracks.

Chapter 5

Operation and Results

Once the AGC was operational, four sets of tests were run on it. The first set took place in Heinz-Beitz Hall at Nelson Mandela Metropolitan University (NMMU) and was centred on getting the AGC up to the correct operating speed and obtaining some form of line-following control without a towing item being present.

The second set of tests took place at GM Struandale's plant from 29 August to 5 September 2012. These tests were focused on determining the performance of the AGC when towing the required trolley, investigating operating conditions for the specific application, and the design of a suitable layout for the AGC system.

A further set of tests was run at NMMU, designed to provide quantifiable results to determine the ability of the prototype AGC to meet specified requirements.

A final 'buy-off' was done back at GM Struandale from 21 to 23 January 2013. Optimisations were done with the trolley before the AGC was put to test for its intended application. A route was laid down in the plant and several iterations of the route were performed.

5.1 Preliminary Testing

Initial tests with the AGC only were run in the Heinz-Bates Hall at NMMU. The AGC reacted well at low speeds (less than 0.5 $\mathrm{m{\cdot}s^{-1}}$) but slight instability was detected as the speed was increased to the desired operating speed of 1.5 $\mathrm{m{\cdot}s^{-1}}$. These initial tests aimed only to get the AGC to an operational condition; no records were kept of actual performance during this time. The testing was focused on developing the control code for the PLC and programming the various states and requirements for the AGC.

Outcomes from the testing revolved mainly on code optimisations to the PLC and Arduino microcontroller. This was centred on achieving correct interaction between the different

Figure 5.1: CAD Model of an IP Trolley (General Motors South Africa, 2009)

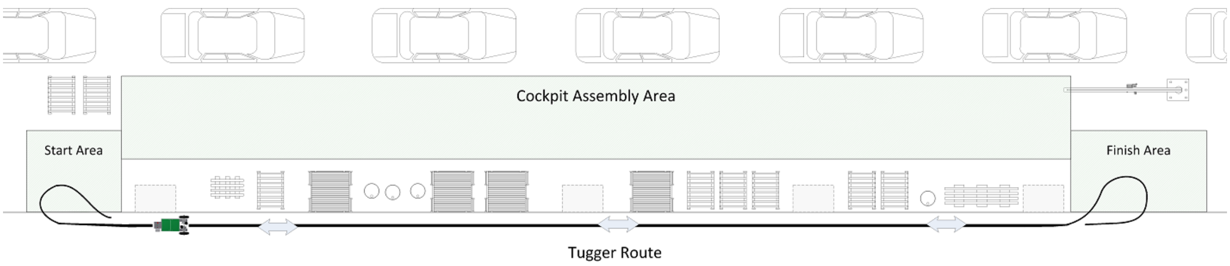


Figure 5.2: Cockpit Assembly Area with Route

units, as well as refining the response of the motor controller. A secondary outcome was to identify any mechanical design flaws, however none of concern were noted.

The next round of testing focused on a specific application at the GM Struandale plant that was suggested. In the General Assembly area, a section is allocated to the building of the dashboard and accessories for two car models. The area makes use of instrument panel trolleys (referred to as IP trolleys, see Figure 5.1) on which the dashboards are assembled. As the trolleys move along the length of the area, the dashboards they carry are assembled in production-line style.

Currently when an IP trolley reaches the end of the line, the dashboard is removed from the trolley and a worker is required to push the trolley back to the start point. A layout of the area can be seen in Figure 5.2.

Although original specifications intended the AGC to be run on a closed loop, the area in question did not lend itself to this. Therefore the route design was altered to accommodate the area. Instead of having a complete loop, two mini loops were joined by a long straight section that runs the length of the cockpit area. The mini loop at each end allows the AGC to turn 180°and return by the same route along which it came. The route layout can be seen in Figure 5.2.

Figure 5.3: Tow Arm Welded to IP Trolley

When the AGC encounters a split in the track, the path it will be directed along will depend on which sensors are active at the time. As such, it could follow a different path each time, making it difficult to get consistent results. To solve this, a gap was left between the intended route of the AGC and its return path, wide enough such that the AGC would not detect it when entering the loop. Therefore on the return loop the AGC is required to cover a short distance where no track is laid.

This is to prevent the AGC from misinterpreting the track it has to follow. Usually this would cause the AGC to shut down as it is indicative of being off track. Taking this into account, a timer was introduced allowing the AGC to travel at the same speed for 2.5 s after losing the track.

The two return loops can be seen in the route layout in Figure 5.2.

5.1.1 AGC and Trolley Modifications

The original AGC design did not include a tow bar, because GMSA had not yet decided on its specific application. Nor did the selected trolleys have any latch to enable them to be towed.

Staff at the GM Struandale workshop made use of a tow arm found on conventional trolleys (used by in-house tuggers), and welded this on to one of the IP trolleys for testing, as shown in Figure 5.3.

To create a tow bar for the AGC a piece of rebar was bent and welded to a length of angle steel which was bolted to the back of the AGC. This can be seen in Figure 5.4.

Changes also had to be made to the wheels of the IP trolley. To assist manoeuvrability of the trolley during normal operation it had been fitted with four castor wheels capable of rotating. Towing an item capable of moving in any direction can cause problems, especially when some resistance is involved in the turning of the trolley's wheels. The most common problem experienced was the entire trolley swinging or drifting out sideways when behind the AGC operating as the towing vehicle.

To solve this problem the two back wheels of the trolley were substituted with fixed castor

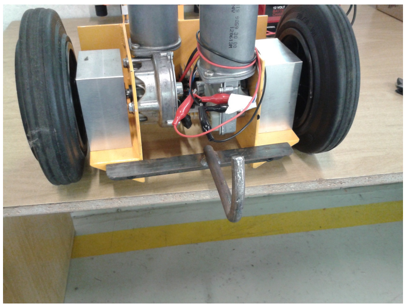


Figure 5.4: Tow Bar Mounted on AGC

(a) Old Rotating Castor Wheel

(b) New Fixed Castor Wheel

Figure 5.5: IP Trolley Wheels

wheels. This stabilised the trolley and enabled it to follow the line of the AGC without swinging out. The old and new wheels can be seen in Figures 5.5a and 5.5b respectively.

5.1.2 Movement Tests

For testing at GM Struandale a small section was allocated where a track could be set up. This was a different area to the intended area of operation of the AGCs as testing in that area would cause interference with the daily running of the plant. The allocated area had similar physical attributes to that of the intended area.

A small route was laid out that included a short straight section and a turn-around loop.

During this testing several factors were noted. When accelerating with the trolley attached, slight slipping occurred on the driving wheels before the AGC acquired enough traction to accelerate. This is possibly because the traction calculations done were for a concrete surface, whereas the actual use surface was had a smooth painted finish. Once moving the AGC demonstrated fairly stable control and was able to follow a straight path.

A second problem occurred when following a curved line. The AGC followed a straight line without any problems. However, when the trolley was attached if a corner was too sharp, the trolley's momentum would push the AGC's backend sideways, causing it to

(a) Trailer Dolly Hongya Trailer (2012) (b) Trolley With Incorporated Dolly Direct Industry (2012)

Figure 5.6: Trailer Steering Mechanisms

jack-knife.

Several factors caused this. Firstly, the speed of the AGC and the large weight differential between the towing and towed objects. Second, on cornering one of the wheels is slowed down while the other's speed is increased. This slowing down of the AGC, along with slight play in the connection between the AGC and the trailer, meant the trailer would only slow down moments later once the slack had been taken up.

In truck/trailer design of similar vehicle dynamics, a dolly is usually used. The dolly acts as the two front wheels of the trailer which would turn together in the direction of the tow bar. As the towing vehicle turns, the front wheels are also turned (see Figures 5.6a and 5.6b). This means that the extra force from turning is placed on the trailer's wheels, as opposed to the driving wheels on the AGC.

As a workaround to the steering issue, the circuit was designed to take this into account. The AGC would travel along the straight section of the route with trolley in tow. When approaching the end loop, a marker before the loop would cause the AGC to stop. The operator would remove the trolley and instruct the AGC to continue. The AGC would then travel the loop and return to fetch a new trolley. At the other end the AGC completes the loop before coming to a halt and waiting for the trolley to be hitched, already facing the correct direction.

Overall the results were satisfactory:

- The AGC was able to navigate the model route used for testing;
- It was capable of towing the trolley at close to the desired speed of 1.5 m$\cdot$s^{-1}. On consultation with GMSA staff onsite, it was suggested that the AGC speed be slightly reduced as the large weight of the trolley could be dangerous at full speed.
- The suggested method of functioning was demonstrated whereby the AGC towed the trolley along the straight section, stopped at one of the RFID markers, had the trolley offloaded and was then sent back via the return loop to fetch another trolley.

A video compilation from the testing can be viewed on the CD attached under Appendix H.3.1.

Figure 5.7: Corner Tracks

5.2 Operation

This section covers the set up procedure for the AGC. This includes how the AGC and the environment should be setup for initial use, covers some software topics and also lists maintenance guidelines.

5.2.1 AGC

The two main parts to the setup, are those affecting the AGC directly, and separately the SCADA setup, as the AGC can be run without the SCADA server being active. The PLC and associated electronics are all setup to start on power-up, requiring only a suitably setup track and correctly connected batteries.

Track

The recommended product for the track is Eclipse 25 mm stainless steel tape. It is sold in 30 m lengths, has a white surface with an adhesive layer on the underside. For corners it is advised to use a pair of tin snips. Starting with a straight section, perpendicular slots should be cut into the strip every 5 cm, leaving a few mm of the tape to hold it together. Depending on the radius of the curve, distances can be altered. The sections of tape can then be angled to form the desired curve. An example is shown in Figure 5.7.

The next step was to install the RFID markers. Only two markers were required per circuit: one when the AGC must stop to offload the trolley, and the second at the other end of the circuit when a trolley needs to be loaded.

Either the small circular or large rectangular markers can be used. Testing indicated similar responses for either marker. It is advised to cut a section of the track to allow the markers to sit flush with the top of the track. Any suitable adhesive can be used.

It is advised that the area be thoroughly cleaned before making use of any adhesive materials. If not clean, the tape tends to come loose after time. Should the track become damaged over time, it may be necessary to replace sections. As an additional protection

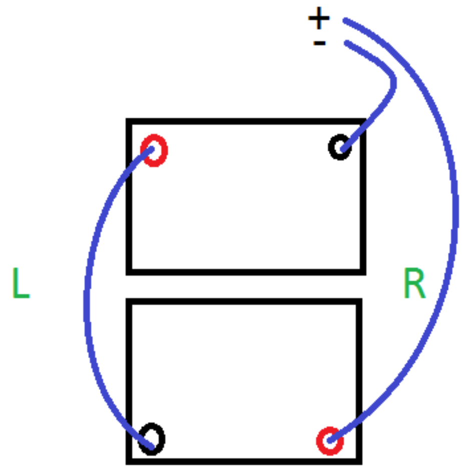


Figure 5.8: Battery Wiring Layout

for the tape, a suitable rubber extrusion can be placed alongside the tape to deter it form coming loose.

Batteries

The two batteries should be placed in the AGC with their terminals located away from each other, to minimise the likelihood of a short occurring.

Before the batteries are connected the system switch must be in the OFF (horizontal) position.

The two terminals on the left hand side of the AGC should be connected. The system ground should be connected to the terminal closest to the front of the AGC, and the positive to the last remaining terminal. The battery terminal connection can be seen in Figure 5.8.

PLC

The PLC is set to start automatically when powered up. To supply power to the PLC, the batteries must be correctly connected and the main power switch is at the ON (vertical) position.

The PLC takes several seconds to start up, and once running, the red light will be illuminated. One can also check the state of the PLC by referring to its indicating lights on the unit itself.

5.2.2 SCADA

Appendix E contains the correct setup method for the SCADA system, as well as debugging instructions. The start-up process is explained below

Wireless

The wireless module in the AGC should have power; this can be monitored by checking the red power LED on the unit in the front electrical box of the AGC. The unit should automatically receive power when the rest of the AGC is powered. The green power LED on the Arduino microcontroller board should also be lit.

The second wireless is plugged into the server computer via the USB adaptor. A red power LED should be illuminated

WAMP

The WAMP software package runs on the server computer. When running correctly a green 'W' is visible in the computer's notification area.

Logging and Monitoring

To start the logging and serial connection of the system, the python script (*sqlserial.py*) needs to be run on the server. When running a console is visible that can be monitored for debugging purposes. It will indicate if there are problems with the serial or database connections and also display any data being received on the serial port.

Web interface

The web interface for the SCADA can be viewed by accessing *http://<server IP address>/scada* from a standard web browser on any device connected to the same network as the server.

5.2.3 Maintenance

The AGC was developed to require minimum maintenance on a daily basis, but several aspects should be checked regularly to ensure continued functioning.

Battery Maintenance

The batteries selected for testing are sealed, maintenance-free batteries. This means that it is not possible to top-up the batteries' water levels as with some other commonly found batteries. If the batteries are replaced at a later stage with serviceable batteries then both the level of electrolyte and the specific gravity of the electrolyte should be tested. Regardless, it is advised that checks be conducted regularly for battery leaks and for precipitate build-up on the battery terminals. If there are concerns with the quality of the battery supply (low, voltage, quick discharge) then specific battery testers can be used.

While the batteries used in testing were standard car 'starter' batteries, the use of deep-cycle batteries is suggested (as discussed in Section 3.3.1). The expected life of the current batteries is only six months with regular charge/discharge cycles, suitable for testing but not for normal production use.

Track Maintenance

The track should be checked once a week, or whenever a reoccurring line-following fault occurs, to ensure that sections have not been damaged. This should include checking of RFID tags for correct placement and potential damage.

Computer Maintenance

Maintenance of the SCADA system is limited to the correct functioning of the server computer. Data backups should be structured to align with corporate IT policies of the company.

Bearing maintenance

The AGC is fitted with four SKF 6305-2RS1 deep groove ball bearings. The bearings are sealed and require no maintenance. The bearings are rated at 23.5 kN dynamic load and limited to 7 500 RPM, both of these being far higher than required. According to the SKF's online bearing life calculator (SKF, 2012), the bearing should last in excess of 1 000 000 hours. The same value was calculated for the grease life in the sealed unit.

This far exceeds the expected life span of the AGC. However it is advised to monitor the bearings on an annual basis to determine if replacing is required.

Wheel maintenance

The shafts that the wheels rotate upon are held in place by a nut that pushes up against the outside of the bearings. A small grub screw (located on the large end of the shaft) locks the rotation of the shaft, to the motor shaft.

The wheel is held in place by a second nut that screws onto the small end of the shaft. A bolt that goes through each wheel comes up against a flat section of the shaft. This locks the rotation of the wheel to the shaft.

Each of these connections should be monitored on a daily basis to ensure that they remain tight during operation. Should loosening be noted on a regular basis a suitable Loctite or other similar product should be applied to the offending fastener.

5.3 Capability Testing

Endurance testing of the AGC took place in the new engineering building at NMMU. Logistical problems meant that the trolley was not available for this testing, but sufficient data from previous testing ensured that this was not an issue.

To test the system a route would be set up and the AGC be made to repeat this track for an extended time. During this time the various AGC components would be tested. The total time that the AGC ran for would be recorded along with all reliability issues that occurred.

During final testing the AGC was run for 13 hours over a period of 3 days. It was run on an oval track (as initially set out in the design requirements) of 12 m in length by 4 m wide. This route included stops at three markers with different configurations: stops via the remote control, stops as a result of obstructions and emergency stops. At the end of the first day the unit was charged in preparation for the next day's testing; however to test if the batteries would last a whole shift, they were not charged between the second and third day's testing.

A video compilation from the testing can be viewed on the CD attached under Appendix H.3.2.

5.3.1 Running Time

Table 5.1 logs the amount of time that the unit ran for each day during testing. During each testing period the unit was constantly in use. The product was designed to run for at least 8 hours without requiring a recharge. The test result shows that the running time was significantly exceeded. This is as expected when compared of the initial design requirements for the battery selection.

5.3.2 RFID

Some problems were experienced when the AGC came to a marker and failed to stop. Monitoring the SCADA system showed this was as a result of the RFID reader not being in range of the markers, and not a fault with communication between the reader and the AGC. By observing the AGC as it passed over markers it was possible to see that the winding path the AGC followed would sometimes result in the RFID reader going around a marker.

Three different marker setups were tested. One made use of two rectangular markers placed alongside the track, one with two circular markers, and one with three circular markers.

While moving the AGC generally exhibited one of two kinds of straight line movement: the first being more controlled (less lateral movement) than the second. The more controlled movement would result in only the inner three induction sensors being activated (three-sensor movement); the second movement resulted in all five of the AGC's sensors being individually activated at some stage (five-sensor movement).

If the AGC was exhibiting three-sensor movement it would only miss a marker set once per five loops (94% reliability). If the AGC's movement was activating all five sensors, the RFID unit would miss one marker in every two loops (88% reliability).

If the AGC were to not stop at a marker, this could lead to problems and potential damage. As such 100% reliability under normal operating conditions is required. Several ways to solve this problem are discussed in Section 6.1.6, although time constraints did not allow for testing of these potential solutions.

5.3.3 Charger

The standard battery chargers were connected at the end of the day 1. By the time testing was required to start the next day the batteries were fully charged. The time between the start of charging and the start of the next day's shift was roughly 8 hours. It must be noted that the AGC was run by itself, and not required to tow a trolley during these tests. The extra weight of a trolley would put more strain on the motors meaning more energy drawn from the batteries.

5.3.4 Safety

To test the reliability of the bumper, it was activated on average once every five loops that the AGC made. Whenever this occurred the AGC immediately came to a halt, the red

Table 5.1: Running Times that Occurred During Testing.

day	time
1	3 hr 30 min
2	6 hr 0 min
3	4 hr 0 min

light would begin to flash and the unit could not be reactivated until the bumper switch was reset. The unit responded correctly every time.

The emergency stop button was also activated repeatedly during testing. Each time it was activated, either from the remote or the button on the AGC, the AGC would respond correctly; in the same fashion as when the bumper was activated.

In a similar fashion an obstruction was placed in the path of the AGC once every five loops. This obstruction was large enough to be detected by the IR proximity sensor and placed in a position that would enable it to be detected.

Sometimes the obstruction was moved across the path of the AGC in a manner of a person walking in front of it, and other times the obstruction would be left in the path as if a box had been placed in its way.

Each time the AGC would come to a halt a short distance from the obstruction (distance was dependent on the colour and texture of the object). The sensor had a sensing range of up to 0.8 m. The AGC would travel at most 0.1 m after an obstruction was detected, mainly due to inertia. The AGC would not continue on its route until the obstruction was removed. At this point the startup procedure would commence and the AGC would continue on its route after 2.5 s.

In the prototype only one IR proximity sensor was used. This gave the AGC a limited field of vision. If more sensors are to be used care must be taken to calibrate the sensors on the route the AGC will be used on so that pillars and other stationary objects which may activate the sensors are out of range of the AGC.

At several times during testing the AGC was physically manoeuvred off-course; each time this occurred the AGC stopped after 2.5 s. This was done several times a day at random intervals.

5.3.5 Wireless

The wireless units used during testing were the low power units of the product range, with expected range of 40 m line of sight. During testing the AGC was never further than 30 m away from the receiving unit (plugged into the server) and from the results, there is no indication that any problems with the wireless communication occurred.

A brief test was done to determine the range of the units in their current configuration, and errors in communication were noted when the AGC was located more than 50 m away from the server.

As has been mentioned, a high power unit (XBee Pro range) can be purchased which is a pin-for-pin replacement of the standard model. The Pro version boosts the possible range to more than 1 km and will allow stable communication indoors of several hundred meters, should this be required.

5.3.6 Line Following

The AGC's ability to follow a line is difficult to quantify. Sensor readings do not give the displacement from the line, thus all it is possible to do is to describe its motion.

During the testing, the AGC successfully navigated the track at a straight line speed of about 0.5 $\mathrm{m{\cdot}s^{-1}}$.

Movement in a straight line was fairly stable, with generally only the centre three induction sensors being activated (equivalent to 8.7° of motion). At times some overshoot would occur and the outer sensors would be activated giving the AGC a slightly wider swing (17.5° of motion), but remaining on track.

When coming out of a corner the AGC would have equal chances of being in a state of three- or five-sensor activation movement. If it was in five-sensor movement, it generally would not recover to three-sensor movement until completing a further corner. It was possible to stabilise the AGC and regain three-sensor movement by physically preventing it from overshooting and letting it continue.

During the three days of testing (14 hours of run time), under normal circumstances the AGC only came to a halt as a result of losing the track on five occasions. Each time this occurred when the AGC was driving in a straight line and no oscillation was taking place. This was caused due to the distance between the sensors. It is possible that in driving in a straight line, none of the sensors (with radius 15 mm and spaced 50 mm apart) are active as the track (width 25 mm) is in between two sensors. A resulting overlap of sensor and track of less than 4 mm would not activate the sensor. When this happened the AGC came to a stop and would only continue once instructed to do so.

5.4 Final Testing

Final testing took place at the GM Struandale plant. These tests were to confirm the AGC's capabilities. Initially testing was done in a small area, allowing for fine tuning, but on the final day, after production at the facility had stopped, the track was set up in the manner for which the AGC was designed.

First, repeatability studies were done on a shorter track consisting of a 5 m straight section with one of the designed return loops incorporated.

The track was then laid out as in Figure 5.2. The AGC was allowed to run the route in both directions without the trolley. The times for the track can be seen in Table 5.2.

Overall the AGC did well: it

- successfully navigated the entire route without incident;
- stopped at the markers as required (although from previous testing it was known that markers could be missed); and
- covered the full return route well within the takt time of 4 minutes.

As a result of this and to improve movement and safety it was suggested by the GMSA staff that the AGC be allowed to run at a slower speed. During the testing the SCADA data from the AGC on the laptop running the required software could also be observed.

5.5 Final Costs

A breakdown of the entire cost of the prototype can be found in Appendix B. The major cost products are listed in Table 5.3.

The prototype cost R 26 340, compared to the expected cost of R 25 300. Although these prices are fairly similar, the distribution of costs varies in certain instances. With the use of a PLC over a microcontroller the controller costs were over three times higher than expected. By contrast there was a large drop in expected miscellaneous costs.

A further R 5 000 should be budgeted for the cost to assemble the AGC. It should not take more than 3 days to build one from the already machined components. This cost is based on 8 hours per day at R 200 per hour.

The manufacture of multiple AGCs could result in the cost reducing by a further R 1 000 - R 2 000 per unit. However proposed improvements to the design would result in a zero offset.

Table 5.2: Results of Real-World Application

Test	Time
Loaded	1m22s
Unloaded	1m07s

Table 5.3: The Cost of Several Major Components

Item		Price
Motors	R	4 100
Batteries	R	1 930
Sensors	R	3 000
Controller	R	5 400
Body	R	4 350
Total		**18 780**

Chapter 6

Recommendations and Conclusion

This dissertation documents the steps followed in the development of an AGC. The AGC was designed for a specific application and GMSA stipulated the requirements regarding the capabilities of the AGC. Throughout the development of the AGC these requirements were used to ensure components selected would result in a viable product. Once the design was complete a working prototype of the design was built. This prototype enabled the testing of the proposed design and comparison of results against expected performance. Several sets of tests were run with the results showing a design capable of meeting all given specifications. Some factors need further attention to further promote reliability, and several areas were identified to improve the overall design.

This chapter lists several recommendations for future work and ends with a comparison of the original goals against the achieved results.

6.1 Recommendations

The project revealed several areas that are open for improvement, or could be used to extend the project. During the design phase a priority was placed on choosing low cost items that met the specifications. Because of the fairly linear method of component selection it was difficult to know how much could be spent on each product; even though a budget was established not all items aligned with their budgeted costs. Given that the final design came in under budget, it is possible to suggest upgrades to certain components that could improve reliability and functionality but will result in a higher cost.

6.1.1 Body

As the project progressed, several modifications were made to the design to allow for the addition of extra components. Along with these it is suggested that the AGCs size be increased slightly, specifically the electronics box at the front of the AGC because it is difficult to work in due to its small size. Extending this forward and making it slightly wider permits easier maintenance and assembly of the AGC.

Other recommended body modifications are:

- Enlarging the motor mounting holes to allow for height discrepancies between the motor shaft and the bearing mounts;
- Enlarging the hole for the motor shaft to assist in assembly (the small distance between the motors makes it difficult to install them);
- The modification of several of the steel sheets to include jigsaw puzzle-type connections for easier assembly;
- Fixed mounting posts for the bumper;
- Place to mount conduit for cables that must travel from the front to the back of the AGC;
- A perspex cover for the batteries, both for aesthetic reasons and as a protective device;
- The slight lengthening of the wheel shafts to allow a better fit for the nuts; and
- Replacing the four screws for the lid with a hinge.

Most of these suggested and performed modifications have been modelled; an updated assembly is presented in Appendix D. Digital copies of all manufacturing drawings for the prototype are contained in Appendix H.2 on the attached CD.

6.1.2 Traction

Some slipping is visible when the AGC accelerates from a standstill. It is more noticeable when the trolley is attached. Even though the AGC tends to straighten out quickly once a steady speed is reached, increasing the traction will benefit the performance of the AGC. It should be noted however that the current design does permit the AGC to function correctly, and that these recommendations aim only to improve the design.

Traction also became an issue when turning corners of a radius < 1 m. The AGC itself would respond accordingly and proceed in the correct direction, but the trolley, with far greater inertia, would continue in its current direction. This would often end up pushing the AGC sideways, and causing the combination to jack-knife. This problem was solved by approaching the circuit design, keeping this constraint in mind.

While the material that a wheel comprises of has a large influence on traction, the wheels in use are made of a soft rubber with relatively high co-efficient of friction compared to other products. A change in material is not expected to improve traction.

Another way to increase traction is to increase the weight supported by the driving wheels. The two batteries make up the majority of the weight of the current design. The remainder of the weight is more or less evenly distributed in the frame and other components. Unfortunately the placement of the motors and supporting structure prevent the batteries being relocated.

The modifications to the AGC suggested in Section 6.1.1 will improve traction slightly. The lengthening of the AGC will both increase the weight of the AGC, and move its centre of gravity relatively closer to the rear, placing more weight on the driving wheels. An extension to the length of the AGC of 100 mm (as proposed) will result in a 10% increase in traction.

The easiest way to increase traction is with the use of weights (as seen in farm tractors where weights at the front ensure front tyre grip), however this can have negative impact on performance as the overall weight of the AGC is increased.

6.1.3 Motors

The motor selected was chosen to operate at a certain speed, requiring the development of a certain amount of torque. With the decrease of the desired driving speed, it is suggested that a motor more suited to the new requirements be selected. The selected motors operated well in the application although not originally designed for this use. Although DOGA don't offer a product with higher torque at an appropriate speed in their brochures, they are able to supply customised motors. Using the same motor with a different gearing would enable a higher torque output.

Alternatively motors used in applications such as golf carts can be reinvestigated as they may be more suited to the continuous driving application; however their relative size and cost originally put them out of the scope of this project.

6.1.4 Motor Controller

The Sabertooth controller that was chosen was not designed specifically with industrial use in mind. Nevertheless it fared well during trials. Even during extended testing in excess of the 8 hour shift pattern required, it did not fail, or cut-out. Trials however, could not replicate the daily repetitive use for days and weeks on end.

There is simply no knowledge as to how the product will fair over extended time periods. However there is no expectation that the controller would fail under continuous use as long as it is not strained beyond its design parameters.

It is advised that, going forward, should the cost of the AGC be held at its current rate, the same controller be used on a single unit as its capability is known. The controller has limited settings, and a replacement can be quickly fitted should failure occur during production. The cost of using a different controller would result in an increase in the overall AGC price of roughly 12%.

It's difficult to put a likelihood on the unit failing; however if new motors are to be selected, the performance of this controller must be compared with the required specifications of the new motors. RS Components manufactures two drivers which may be suitable: one capable of supplying 24 A to a single motor (cost: R 2 300 per unit), the second of supplying 32 A and costing R 3 100 per unit (RS Components, 2012*c*). Each unit is only capable of driving one motor.

6.1.5 PLC

Several problems were encountered while trying to implement the PLC. One of the larger issues was the lack of support for the structured text language. The AGC is a fairly complex system, and the researcher often felt that ladder programming did not offer the flexibility that STL or other alternatives would. This, linked with the serial limitations on the Twido, leads to the suggestion of replacing it with a more advanced controller.

Remaining with Telemecanique products, the Modicon M340 Micro PLC range is suggested. A BMXP342010 processor linked with the following modules would be sufficient: a BMXAMO0210 dual analogue output module for motor control; a BMXDDM3202K, 16 input, 16 output module; and a BMXCPS2010 24 V power supply module. The CPU also includes a RJ45 port which can be set up for RS232 serial communication to link the PLC with the RFID and wireless modules. More importantly the processor and programming software support STL.

Better control of the AGC would be possible with this configuration of products, and the need for an Arduino and MAX232 converter would be removed.

Other manufacturers also have controllers that would meet the requirements for the AGC.

6.1.6 RFID

As has been discussed the reliability of the RFID system was lacking. A potential way to improve its reliability is to move the unit to the back of the AGC. The prototype had the RFID unit mounted near the front of the AGC, where the AGC had its highest deviation from the track, meaning it is most likely to miss markers. By moving the reader to the back of the AGC it is less likely to miss the markers. During testing the track was always well within the boundaries of the two driving wheels, where the markers are located.

Alternatively a RFID reader with a larger antenna could be used. Using a device with a wide antenna (as long as the width of the AGC, as illustrated in Figure 6.1) would

Figure 6.1: Long RFID Antenna (Impinj, 2012)

Figure 6.2: Siemens Industrial RFID Unit (Siemens, 2012*b*)

guarantee picking up the markers. The disadvantage with this is the expected higher costs

The RFID unit used in this project was chosen for its small form, low cost and ease of use but again this unit is not specifically designed to operate in an industrial environment. If a larger budget were approved, an industrial unit is suggested. All the major automation manufacturers supply RFID units and a product such as Siemens Moby D unit (pictured in Figure 6.2) would be appropriate.

If neither of these options is viable a simple solution could be developed by placing unusual patterns at stop points. These patterns, made out of metal, would activate certain of the induction sensors in a manner uncharacteristic of the track it follows, which would indicate a stop point. However, this would remove the locational awareness aspect of the AGC as only a few different patterns would be possible.

6.1.7 Batteries

Although the supplied batteries were sufficient for use in the prototype, investigations into the use of deep-cycle lead-acid batteries should be performed. These batteries, often found in solar and wind generation systems, cost approximately twice as much as conventional starter batteries (such as used in the prototype), but are designed to better handle the continual charge-discharge cycle. . They are also the standard battery type used in forklifts and tuggers for indoor industrial use and would be well-suited to the application.

Deep-cycle batteries also have a higher lead content per Amp-hour as well as an associated increase in weight. However, from the a design perspective it was known that the batteries selected for the prototype had an Amp-hour rating far higher than was required for operation; therefore batteries with a lower capacity could be selected.

6.1.8 Charging

Minor charging issues were encountered because of the apparent non-isolation of multiple charging circuits. The selection of new batteries requirse a reevaluation of the charger. In the current state the charger could be replaced with a single 24 V lead-acid battery charger.

As an extension of the current project, a method for automatically charging the AGC could be developed. This would entail the automatic driving of the AGC to a charging station at a certain time, or the inclusion of a station located along the track, where it could charge when not in use.

6.2 Objectives Comparison

GMSA gave positive feedback that the final product fulfilled their brief and was successfully demonstrated. Comparing the list of objectives and what was achieved, the following is noteworthy.

Comprehensive research was done on a wide variety of topics which had an impact on the different design factors of the AGC. The research helped identify alternate solutions for each factor and provided information regarding which solution was best.

Several meetings were held with staff at GMSA to establish their requirements for the project. Later meetings were held to keep them updated and ensure the final product complied with their specifications.

An AGC design that was completed by GM Thailand was evaluated. Although the design may have been feasible, it was felt that insufficient data supplied, coupled with a high price, made it risky to use the design. However certain elements of this design were drawn on when confirming the current design.

Chapters 3 and 4 described the full procedure followed in the evaluation and development of products for the AGC. This included the determination of specifications for certain products, reasons for selecting one component over another, the development of appropriate software and the system design as a whole.

All the designed components were manufactured and the specified components bought. With these parts a prototype of the AGC was built. Tests were run on the prototype to determine its level of ability.

The AGC functioned as set out in Section 5.3. While the AGC worked well in most respects, the researcher felt that several improvements could be made to improve the overall control and reliability of the AGC.

A SCADA system was developed that functioned well. It gave a good overview of the system at any time. By making use of standard database technology it should permit easy integration into current commercial SCADA systems, or it could be run as a standalone product.

The AGC met the following requirements set out by GMSA:

- It can run for an entire shift with minimal intervention.
- It only requires charging off-shift.
- It is able to navigate a track autonomously.
- Although capable of travelling at walking speed, a request to make this slower was implemented.
- It can tow loads not exceeding 200 kg.
- It was built within size specifications.
- The control interface was accessible at the front of the AGC, but required bending down to interact with it. As a solution a wireless remote control was provided.
- The AGC included several safety mechanisms.

The three main problems noted were:

- The AGC could not stop 100% reliably at markers using the current system; therefore alternatives have been recommended.
- A jack-knife can occur when attempting to traverse a bend while towing a trolley; however it is possible to design a circuit around this constraint. Trolley modifications can also be investigated.
- The initial charging system failed but a simple alternative was identified.

It is important to note that the AGC was produced a final cost of R 26 340, well below the approved budget of R 35 000 per unit, allowing for further upgrades if required. GMSA also provided feedback that the project fulfilled their brief and formed an excellent base for further development (see letter in Appendix G).

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Appendix A

Project Timeline

Table A.1 indicates the time schedule for the project as set out in the proposal and also gives the actual time taken to complete tasks.

A leave of absence taken from mid-September till mid-December meant that several of the tasks were pushed back. Further to this additional modelling of the system took place at the end of the project to try improve the line following stability of the system. This was not initially planned. From May 2013 until November 2014, work was performed on a part-time basis only.

Table A.1: List of Project Tasks and Durations

ID	Task	Planned	Actual
1	Project Proposal	Feb - Mar 2012	Feb - Mar 2012
2	Initial Design	Mar - May 2012	Mar - May 2012
3	Design Review	Mid May 2012	End May 2012
4	Design Alterations	May 2012	Jun 2012
5	Design Review	End May 2012	Mid Jun 2012
6	Component Acquisition	May - Jul 2012	May - Jul 2012
7	Assembly	Jun - Aug 2012	Jun - Aug 2012
8	Programming	Jun - Sep 2012	Jun - Dec 2012
9	Revisions	Sep 2012	Sep - Dec 2012
10	Dissertation Writing	Oct - Nov 2012	Oct 2012 - Jan 2013
11	System Modelling		May - Nov 2013
12	Add. Dissertation Work		Oct 2013 - Nov 2014

Appendix B

Cost Breakdown

From the research and manufacture of the project, the expected and actual costs for the AGC are laid out in table B.1. The prototype was expected to cost R 25 300 with the actual cost coming in at R 26 340.

At the end of the project it was possible to add the actual costs of components and add additional components to the project bill of materials (BOM). Also note that the prices below exclude the required programming cable for the Twido PLC which cost R 2 300.00.

Table B.1: List of AGC Components and Expected vs. Actual Spending. Prices are Rounded Off for Convenience

Part	Expected (R)	Actual (R)
Batteries	2 500	1 930
Motors	4 500	4 100
Motor Controller	2 300	1 600
Induction Sensors	1 000	3 000
Proximity Sensors	3 000	600
Controller etc.	1 500	5 400
Wheels	1 000	390
Tow Pin Assembly	500	-
Body	4 000	4 350
Bearings	-	380
Misecellaneous	4 000	1 600
Battery Chargers	500	1 000
Magnetic Tape	500	700
Sub-Total	**25 300**	**25 050**
SCADA - RFID	-	340
Wireless Server	-	535
Wireless Client	-	415
Total		**26 340**

Appendix C

Electronic Wiring Diagram

Figure C.1 shows a schematic layout of the wiring of all electronic components in the project.

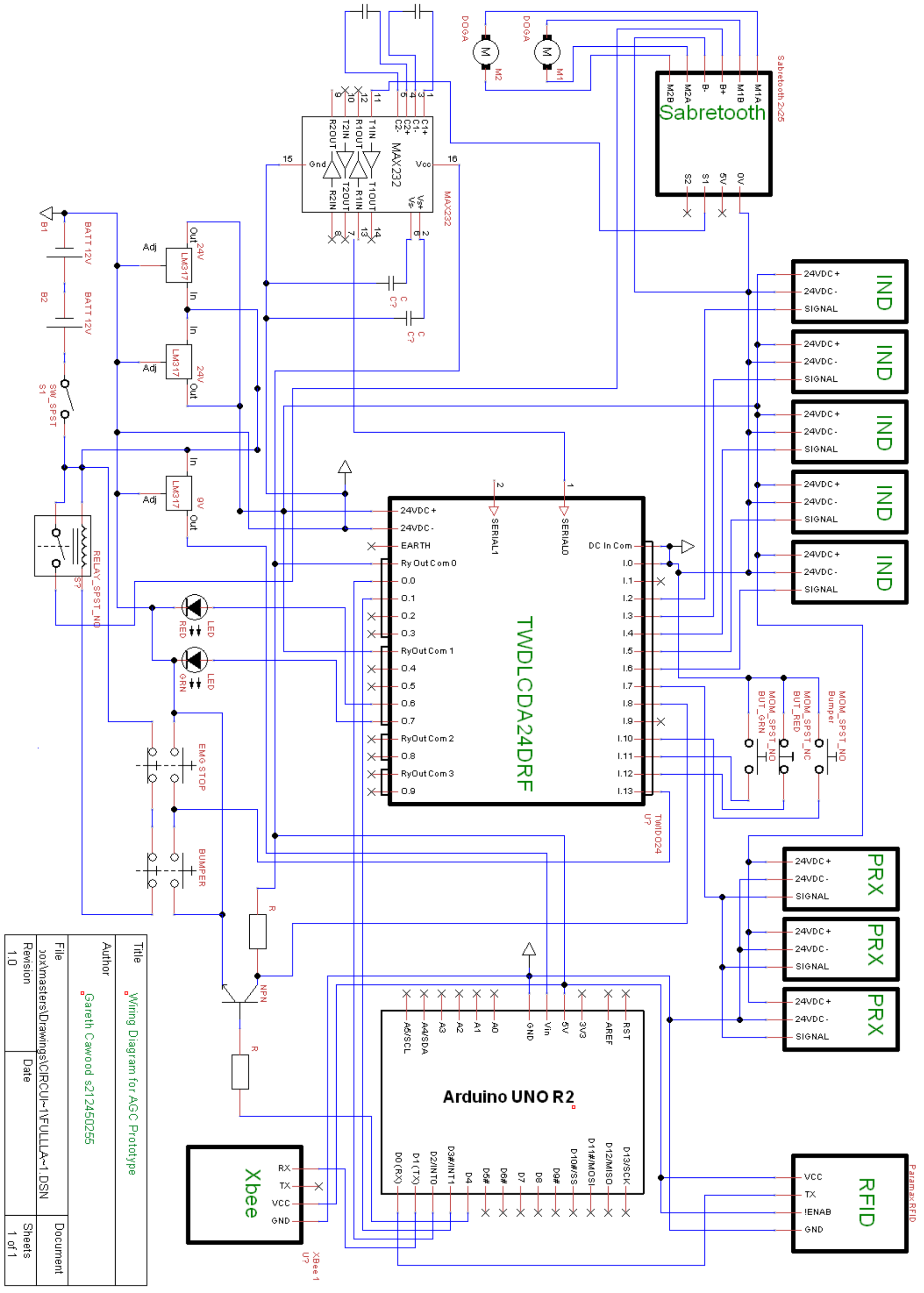


Figure C.1: Wiring Schematic of AGC

Appendix D

CAD Models

Figure D.1 depicts the updated model on the left and the old model on the right.

The new model has been lengthened, the bumper, sensor array, PLC and several buttons and lights have all been modelled. The electronics box at the front of the AGC has been widened slightly, and is now offset so that there is still enough place for the PLC.

Figure D.2 shows an isometric view of the updated AGC.

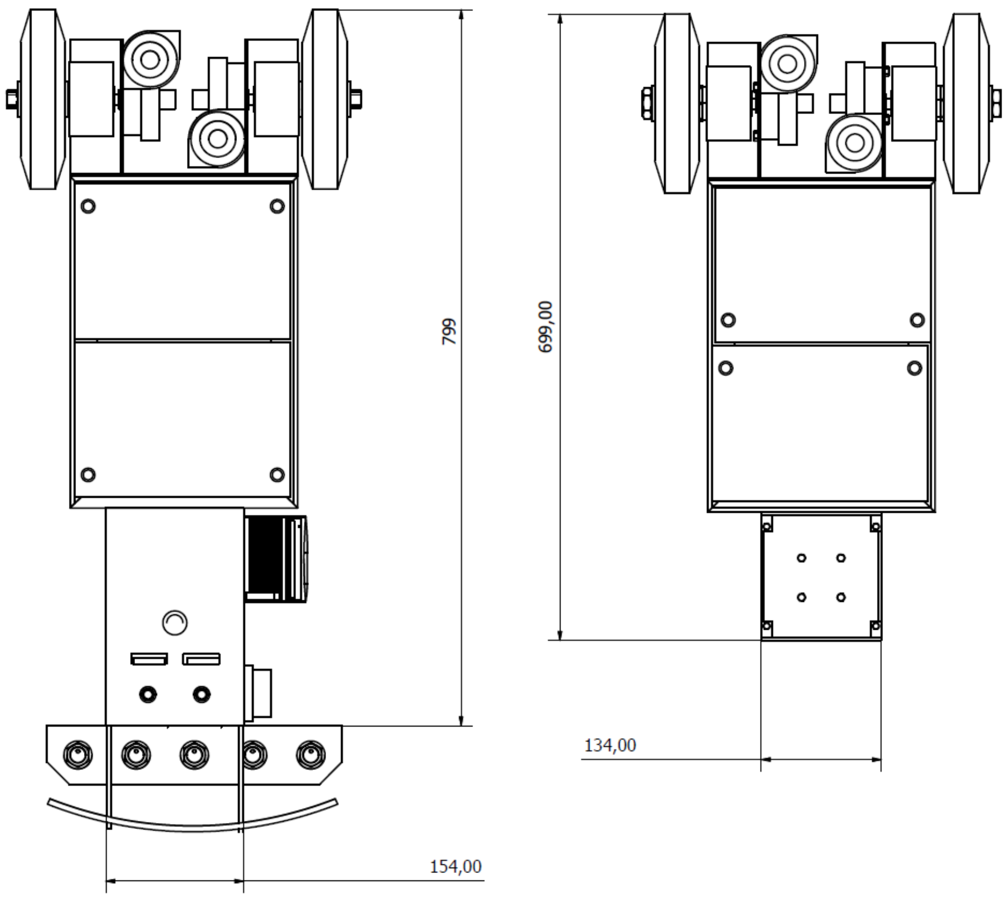


Figure D.1: The Updated and Original AGC Designs

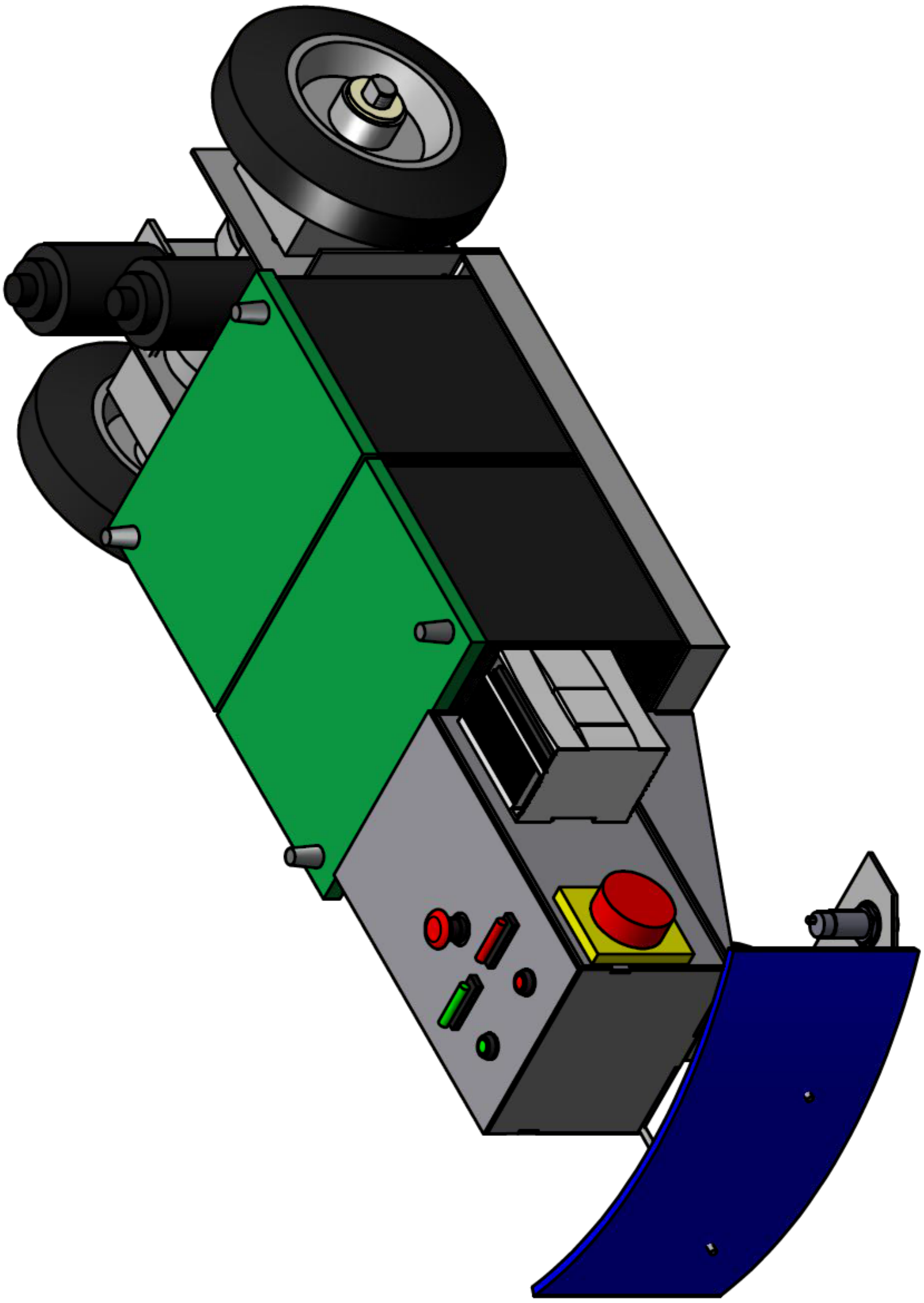


Figure D.2: Isometric View of AGC

Appendix E

SCADA Setup

This appendix highlights the steps that need to be followed to setup the SCADA system on a Windows based PC. The steps should be sufficient that one would be able to set up the system on a different operating system as well.

E.1 Xbee unit

Each XBee unit needs to be plugged into the computer to set it up for correct communication. An XBee USB Xplorer is required for this action. Plug the XBee in question into the Xplorer, and plug the Xplorer into a computer. Depending on the Xplorer model, this may require a USB mini cable.

Install the Digi X-CTU software which can be found on Digi's website.

Run the X-CTU.exe file.

You should be presented with a list of Com ports currently active on the computer you're using. If none are listed you may require extra drivers and the computer's *Device Manager* or equivalent should be referenced.

If several Com ports are listed, one needs to determine which one is the correct one for the XBee. With Baud set at 9600, Flow Control on NONE, Data Bits on 8, Parity on None and Stop Bits on 1, click *Test / Query* on each Com port until a test is successful. This will indicate that the correct Com port is selected. If none of the Com ports are successful it's possible that the unit has already been configured to other settings and further support should be requested.

With the successful Com port selected, click the *Modem Configuration* tab at the top of the window. Click the *Read* button under *Modem Parameter and Firmware.* Once read find the setting for baud rate and set this to 2400 bps. Click *Write.*

If you now attempt to read the data it should fail. Going back to the *PC Settings* tab and setting the baud rate to 2400 should allow for a successful test.

This process needs to be performed on each XBee unit to be used in the system.

E.2 Python

Initially the Python RTE needs to be installed on the system. An installation file can be downloaded from the Python organisation's website. It is necessary to install the latest version of Python 2 and, regardless of the operating system, the 32 bit version must be installed. Currently the latest version is Python 2.7.3.

After this and the following two libraries are installed, the Python code file (*serialtosql.py*) can be run directly from windows.

E.2.1 SQL

For the SQl integration the MySQL Python library was required. The version used in testing was 1.2.3. A Windows 32 bit installer is available for download. The installer must be run and the set up procedure followed.

E.2.2 Serial

A library for serial communication must also be installed. The library, *pyserial* is available to download in a windows installer. The version used during testing was version 2.6. After this library is installed Python setup is complete.

E.3 WAMP

To install WAMP an installer is available from their website. Once installed and running a database structure must be created. To do this open a browser and navigate to *localhost*. Click on *phpmyadmin* under *Tools*.

The following instructions are for the default values as specified in the original Python and PHP files. If values are used that are different to those specified below it will require the editing of all Python and PHP files to ensure correct usernames, passwords and field names.

Create a new database called *agv_scada*. In this database create three tables, *agv*, *log* and *points*.

The *agv* database has the following fields:

- id - int(11) - AUTO_INCREMENT
- agv - varchar(5)
- state - tinyint(1)
- lastpoint - varchar(10)
- error - varchar(5)
- comments - varchar(80)
- statedate - timestamp - CURRENT_TIMESTAMP - ON UPDATE CURRENT_TIMESTAMP
- pointdate - timestamp

The *log* database has the following fields:

- id - int(11) - AUTO_INCREMENT
- date - timestamp - CURRENT_TIMESTAMP - ON UPDATE CURRENT_TIMESTAMP
- agv - varchar(5)
- point - varchar(10)
- state - tinyint(1)

And the *points* database has the following fields:

- id - int(11) - AUTO_INCREMENT
- point - varchar(10)
- comments - varchar(80)
- lastactive - timestamp - CURRENT_TIMESTAMP - ON UPDATE CURRENT_TIMESTAMP

Appendix F

Datasheets

F.1 DOGA Motor Catalogue

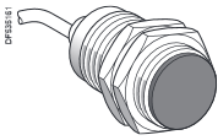
Figure F.1 shows the applicable page from the DOGA motor catalogue.

REFERENCIA REFERENCE NUMBER RÉFERENCE REFERENZNUMMERN	TENSIÓN NOMINAL NOMINAL VOLTAGE TENSION NOMINALE NENNSPANNUNG	PAR NOMINAL NOMINAL TORQUE COUPLE NOMINAL DREHMOMENT NOMINAL	VELOCIDAD NOMINAL NOMINAL SPEED VITESSE NOMINALE GESCHWINDIGKEIT NOMINAL	CORRIENTE NOMINAL NOMINAL CURRENT COURANT NOMINAL NOMINALSTROM	PAR DE ARRANQUE STARTING TORQUE COUPLE DE DÉMARRAGE ANZUGSDREHMOMENT	CORRIENTE DE ARRANQUE STARTING CURRENT COURANT DE DÉMARRAGE ANLAUFSTROM	EJE SHAFT ARBRE WELLE	CONEXIONES CONNECTIONS CONNEXIONS ANSCHLUSSART	ESQUEMA ELÉCTRICO WIRING DIAGRAM SCHÉME ÉLECTRIQUE SCHALTBILD	RELACIÓN DE REDUCCIÓN TRANSMISSION RATIO RAPPORT DE RÉDUCTEUR ÜBERSETZUNG	PESO APROXIMADO APPROXIMATE WEIGHT POIDS APPROXIMATIF GEWICHT (ca.)	GRADO DE ESTANQUEIDAD WATERTIGHTNESS ETANCHÉITE FEUCHTIGKEITSSCHUTZKLASSE	MATERIAL RUEDA WHEEL MATERIAL MATÉRIAU ROUE MAT. DES SCHNECKENRADES	DISEÑO: A,B,C DESIGN: A,B,C DESSIN: A,B,C ABBILDUNG: A,B,C	CURVA CURVE COURBE KURVE
	Un (V)	Mn (N.m./lbf.in)	nn (r.p.m.)	In (A)	Ma (N.m./lbf.in)	Ia (A)				i	P (kg/lb.t)	IP			
319.1846.20.00	12	4 / 35	85	7	40 / 354	60	E35	C37	F5	78:2	1.7 / 4.55	IP55	PLA	a	62
319.1846.30.00	24	4 / 35	85	3.5	40 / 354	30	E35	C37	F5	78:2	1.7 / 4.55	IP55	PLA	a	62
319.1860.20.00	12	9 / 79.6	30	7	50 / 442	28	E35	C37	F5	81:1	1.7 / 4.55	IP55	PLA	a	58
319.1860.30.00	24	9 / 79.6	30	3	50 / 442	15	E35	C37	F5	81:1	1.7 / 4.55	IP55	PLA	a	58
319.1862.20.00	12	8 / 70.8	45	6	50 / 442	50	E35	C37	F5	81:1	1.7 / 4.55	IP55	PLA	a	60
319.1862.30.00	24	9 / 79.6	45	3	60 / 531	25	E35	C37	F5	81:1	1.7 / 4.55	IP55	PLA	a	61
319.3820.20.00	12	9 / 79.6	30	7	50 / 442	28	E35	C37	EE4	81:1	1.7 / 4.55	IP55	BRO	a	58
319.3820.30.00	24	9 / 79.6	30	3	50 / 442	15	E35	C37	EE4	81:1	1.7 / 4.55	IP55	BRO	a	58
319.3822.20.00	12	8 / 70.8	45	6	50 / 442	50	E35	C37	EE4	81:1	1.7 / 4.55	IP55	BRO	a	60
319.3822.30.00	24	9 / 79.6	45	3	60 / 531	25	E35	C37	EE4	81:1	1.7 / 4.55	IP55	BRO	a	61
319.3845.20.00	12	6 / 53.1	65	8	35 / 309	40	E35	C37	EE4	78:2	1.7 / 4.55	IP55	PLA	a	67
319.3845.30.00	24	6 / 53.1	65	4	40 / 354	25	E35	C37	EE4	78:2	1.7 / 4.55	IP55	PLA	a	67
319.3846.20.00	12	4 / 35	85	7	40 / 354	60	E35	C37	EE4	78:2	1.7 / 4.55	IP55	PLA	a	62
319.3846.30.00	24	4 / 35	85	3.5	40 / 354	30	E35	C37	EE4	78:2	1.7 / 4.55	IP55	PLA	a	62
319.3860.20.00	12	9 / 79.6	30	7	50 / 442	28	E35	C37	EE4	81:1	1.7 / 4.55	IP55	PLA	a	58
319.3860.30.00	24	9 / 79.6	30	3	50 / 442	15	E35	C37	EE4	81:1	1.7 / 4.55	IP55	PLA	a	58
319.3862.20.00	12	8 / 70.8	45	6	50 / 442	50	E35	C37	EE4	81:1	1.7 / 4.55	IP55	PLA	a	60
319.3862.30.00	24	9 / 79.6	45	3	60 / 531	25	E35	C37	EE4	81:1	1.7 / 4.55	IP55	PLA	a	61
319.9059.30.00	24	2.2 / 19.47	230	4	20 / 177	36	E35	C37	EE4	67:4	1.7 / 4.55	IP55	PLA	a	65
319.9128.30.00	24	2.2 / 19.47	230	4	20 / 177	36	E35/E63	C38	EE4	67:4	1.7 / 4.55	IP55	PLA	b	65
319.9137.20.00	12	2 / 17.7	155	8	20 / 177	60	E35	C38	EE4	67:4	1.7 / 4.55	IP55	PLA	a	66
319.9137.30.00	24	2 / 17.7	175	4	20 / 177	30	E35	C38	EE4	67:4	1.7 / 4.55	IP55	PLA	a	66

Figure F.1: DOGA Motor Catalogue (DOGA, 2012)

F.2 Schneider-Electric Sensor Catalogue

Figure F.2 shows the applicable page from the Schneider Electric sensor database.



XS230AA●●L2

Ø 30, threaded M30 x 1.5

Sensing distance (Sn) mm	Function	Output	Connection	Reference	Weight kg
22	NO	PNP	Pre-cabled (L = 2 m) *(1)*	**XS230AAPAL2**	0.140
			M12 connector	**XS230AAPAM12**	0.080
		NPN	Pre-cabled (L = 2 m) *(1)*	**XS230AANAL2**	0.140
			M12 connector	**XS230AANAM12**	0.080

Figure F.2: Schneider Electric Sensor Catalogue (Schneider Electric, 2012a)

F.3 Digi International Xbee Datasheet

Figure F.3 shows the applicable page from the Digi reference documents.

Specifications

Table 1-01. Specifications of the XBee®/XBee-PRO® RF Modules

Specification	XBee	XBee-PRO
Performance		
Indoor/Urban Range	Up to 100 ft (30 m)	Up to 300 ft. (90 m), up to 200 ft (60 m) International variant
Outdoor RF line-of-sight Range	Up to 300 ft (90 m)	Up to 1 mile (1600 m), up to 2500 ft (750 m) international variant
Transmit Power Output (software selectable)	1mW (0 dBm)	63mW (18dBm)* 10mW (10 dBm) for International variant
RF Data Rate	250,000 bps	250,000 bps
Serial Interface Data Rate (software selectable)	1200 bps - 250 kbps (non-standard baud rates also supported)	1200 bps - 250 kbps (non-standard baud rates also supported)
Receiver Sensitivity	-92 dBm (1% packet error rate)	-100 dBm (1% packet error rate)
Power Requirements		
Supply Voltage	2.8 – 3.4 V	2.8 – 3.4 V
Transmit Current (typical)	45mA (@ 3.3 V)	250mA (@3.3 V) (150mA for international variant) RPSMA module only: 340mA (@3.3 V) (180mA for international variant)
Idle / Receive Current (typical)	50mA (@ 3.3 V)	55mA (@ 3.3 V)
Power-down Current	< 10 µA	< 10 µA
General		
Operating Frequency	ISM 2.4 GHz	ISM 2.4 GHz
Dimensions	0.960" x 1.087" (2.438cm x 2.761cm)	0.960" x 1.297" (2.438cm x 3.294cm)
Operating Temperature	-40 to 85° C (industrial)	-40 to 85° C (industrial)
Antenna Options	Integrated Whip, Chip or U.FL Connector, RPSMA Connector	Integrated Whip, Chip or U.FL Connector, RPSMA Connector
Networking & Security		
Supported Network Topologies	Point-to-point, Point-to-multipoint & Peer-to-peer	
Number of Channels (software selectable)	16 Direct Sequence Channels	12 Direct Sequence Channels
Addressing Options	PAN ID, Channel and Addresses	PAN ID, Channel and Addresses
Agency Approvals		
United States (FCC Part 15.247)	OUR-XBEE	OUR-XBEEPRO
Industry Canada (IC)	4214A XBEE	4214A XBEEPRO
Europe (CE)	ETSI	ETSI (Max. 10 dBm transmit power output)*
Japan	R201WW07215214	R201WW08215111 (Max. 10 dBm transmit power output)*
Austraila	C-Tick	C-Tick

Figure F.3: Digi XBee datasheet (Digi International, 2009)

F.4 Schneider-Electric PLC Datasheet

Figure F.4 shows the applicable page from the Schneider-Electric PLC reference documents.

Discrete I/O	Basic	24	40
	Number of inputs	14 sink/source ⎓ 24 V inputs *(1)*	24 sink/source ⎓ 24 V inputs *(1)*
	Number of outputs	10 relay outputs	14 relay outputs 2 source transistor outputs
	Type of connection	By removable screw terminal block	
Expansion I/O	Number of expansion modules	4 modules max. *(2)*	7 modules max. *(2)*
	Discrete I/O modules	15 types of module: input, output, mixed 8, 16, 24, 32 channels, connection by screw or spring terminals or by HE 10 connector	
	Analog I/O modules	10 types of module: input, output, mixed 2, 4 or 8 channels, connection by screw terminals	
	Communication	CANopen bus master module	
Maximum number of I/O per configuration (base controller with I/O expansion modules)		88/120/152 according to whether I/O expansion has: screw terminals*(3)*/spring terminals/HE 10 connector	152/184/248 according to whether I/O expansion has: screw terminals/spring terminals/ HE 10 connector
Functions	PID	Yes	
	Event processing	Yes	
Communication	Integrated	1 RS 485 serial port, 1 optional RS 232C/RS 485 serial port	
			Ethernet port (on TWD LC•E)
	Ethernet TCP/IP	TwidoPort interface module (via RS 485 serial port)	
	Expansion	CANopen	
Supply voltage		∿ 100...240 V for TWD LCA• (⎓ 24 V discrete sensors powered by the base controller), ⎓ 19.2...30 V for TWD LCD•	
Programming	Application memory	3000 instructions	3000 instructions, 6000 with memory extension
	Internal bits	256 bits	
	Internal words *(5)*	3000	
	Standard function blocks *(5)*	128 timers, 128 counters	
	Double words	Yes	Yes
	Floating, Trigonometrical	No	Yes
	Real-time clock	Optional real time clock cartridge, using 16 real-time clock blocks	Integrated
Type of base controller	Standard	**TWD LC•A 24DRF *(6)***	**TWD LC•A 40DRF *(6)***
	With integrated Ethernet port		**TWD LC•E 40DRF *(6)***

Figure F.4: Schneider-Electric PLC datasheet (Schneider Electric, 2011)

F.5 Schneider-Electric Proxy

Figure F.5 shows the applicable page from the Schneider Electric proxy reference documents.

Product datasheet
Characteristics

xub5ananl2
photo-electric sensor - XUB - diffuse - Sn 0.6m - 12..24VDC - cable 2m

Main

Range of product	OsiSense XU
Series name	General purpose single mode
Electronic sensor type	Photo-electric sensor
Sensor name	XUB
Sensor design	Cylindrical M18
Detection system	Diffuse
Material	Plastic
Line of sight type	Axial
Type of output signal	Discrete
Supply circuit type	DC
Wiring technique	3-wire
Discrete output type	NPN
Discrete output function	1 NO
Electrical connection	Cable
Cable length	2 m
Product specific application	-
Emission	Infrared diffuse
[Sn] nominal sensing distance	0.6 m diffuse

Complementary

Enclosure material	PBT
Lens material	PMMA
Maximum sensing distance	0.8 m diffuse
Output type	Solid state
Add on output	Without
Wire insulation material	PvR
Status LED	1 LED (yellow) for output state
[Us] rated supply voltage	12...24 V DC with reverse polarity protection
Supply voltage limits	10...36 V DC
Switching capacity in mA	<= 100 mA (overload and short-circuit protection)
Switching frequency	<= 500 Hz
Voltage drop	1.5 V (closed state)
Current consumption	35 mA (no-load)
Delay first up	< 15 ms
Delay response	< 1 ms
Delay recovery	< 1 ms
Setting-up	Sensitivity adjustment
Diameter	18 mm
Length	62 mm

Figure F.5: Schneider Electric proxy datasheet (Schneider Electric, 2012*c*)

F.6 Datasheets for Miscellaneous Components

Figure F.6 shows the applicable page from the RS Components switch reference documents.

- Back of door mounting load break switch
- Red/Yellow handle padlockable

Dimensions	
Back of panel switch:	
Height	87mm
Width	68mm
Depth	56mm
Handle:	
Height	64mm
Width	64mm
Depth	42mm
Weight	0.265Kg
Features	
Rated operational voltage Ue IEC &EN	690V
Rated operational voltage Ue UL	600V
Rated impulse withstand voltage Uimp	6kV
Rated uninterrupted current Iu	40A
Rated operational current Ie AC22A	40A
Rated operational current Ie AC21A	63A
Rated operational current Ie AC1	63A
Rated operational power AC23A (50/60Hz) 230V	22kW
Rated operational power AC23A (50/60Hz) 415V	30kW
Rated operational power AC23A (50/60Hz) 690V	45kW
Rated operational power AC3 (50/60Hz) 230V	15kW
Rated operational power AC3 (50/60Hz) 415V	18.5kW
Rated operational power AC3 (50/60Hz) 690V	30kW
UL power rating 3 phase DOL 110V	5hp
UL power rating 3 phase DOL 230V	10hp
UL power rating 3 phase DOL 480V	20hp
UL power rating 3 phase DOL 600V	30hp
UL power rating 1 phase DOL 110V	3hp
UL power rating 1 phase DOL 230V	5hp
UL short circuit fuse rating class J	70A
UL rated fused short circuit current	10kA
IEC short circuit capacity max fuse size GI	63A
IEC rated fused short circuit current	30kA
Maximum terminal capacity	25mm^2
Recommended tightening torque	2.0 Nm
Related Products	
Extended main pole + 1NC/1NO auxilliary	LB263EFMC
Extended neutral + 1NC/1NO auxilliary	LB263EFNC
Neutral contact early make/late break	LB263AUXEMFM
Main pole contact	LB263MAINFM
Gasket to provide IP65 rating	LBGASKET

Figure F.6: RS Components switch datasheet (RS Components, 2012*d*)

Figure F.7 shows the applicable page from the Schneider Electric emergency button reference documents.

Product data sheet

Characteristics

XB4BT845

red Ø40 Emergency stop pushbutton Ø22 trigger latching push-pull 1NO+1NC

Complementary

Height	47 mm
Width	40 mm
Depth	82 mm
Terminals description ISO n°1	(13-14)NO
Product weight	0.136 kg
Resistance to high pressure washer	7000000 Pa at 55 °C,distance: 0.1 m
Contacts usage	Standard contacts
Positive opening	With positive opening conforming to EN/IEC 60947-5-1 appendix K
Operating travel	4.3 mm (total travel) 2.6 mm (NO changing electrical state) 1.5 mm (NC changing electrical state)
Operating force	50 N
Mechanical durability	300000 cycles
Tightening torque	0.8...1.2 N.m conforming to EN 60947-1
Shape of screw head	Slotted head compatible with flat Ø 5.5 mm screwdriver Slotted head compatible with flat Ø 4 mm screwdriver Cross head compatible with pozidriv No 1 screwdriver Cross head compatible with Philips no 1 screwdriver
Contacts material	Silver alloy (Ag/Ni)
Short circuit protection	10 A cartridge fuse type gG conforming to EN/IEC 60947-5-1
[Ith] conventional free air thermal current	10 A conforming to EN/IEC 60947-5-1
[Ui] rated insulation voltage	600 V (degree of pollution: 3) conforming to EN 60947-1
[Uimp] rated impulse withstand voltage	6 kV conforming to EN 60947-1
[Ie] rated operational current	1.2 A at 600 V, AC-15, A600 conforming to EN/IEC 60947-5-1 0.55 A at 125 V, DC-13, Q600 conforming to EN/IEC 60947-5-1 0.27 A at 250 V, DC-13, Q600 conforming to EN/IEC 60947-5-1 0.1 A at 600 V, DC-13, Q600 conforming to EN/IEC 60947-5-1 6 A at 120 V, AC-15, A600 conforming to EN/IEC 60947-5-1 3 A at 240 V, AC-15, A600 conforming to EN/IEC 60947-5-1
Electrical durability	1000000 cycles, DC-13, 0.5 A at 24 V, operating rate: 3600 cyc/h, load factor: 0.5 conforming to EN/IEC 60947-5-1 appendix C 1000000 cycles, DC-13, 0.2 A at 110 V, operating rate: 3600 cyc/h, load factor: 0.5 conforming to EN/IEC 60947-5-1 appendix C 1000000 cycles, AC-15, 4 A at 24 V, operating rate: 3600 cyc/h, load factor: 0.5 conforming to EN/IEC 60947-5-1 appendix C 1000000 cycles, AC-15, 3 A at 120 V, operating rate: 3600 cyc/h, load factor: 0.5 conforming to EN/IEC 60947-5-1 appendix C 1000000 cycles, AC-15, 2 A at 230 V, operating rate: 3600 cyc/h, load factor: 0.5 conforming to EN/IEC 60947-5-1 appendix C
Electrical reliability IEC 60947-5-4	Λ < 10exp(-8) at 17 V, 5 mA in clean environment conforming to EN/IEC 60947-5-4 Λ < 10exp(-6) at 5 V, 1 mA in clean environment conforming to EN/IEC 60947-5-4

Figure F.7: Schneider Electric emergency datasheet (Schneider Electric, 2012*b*)

Figure F.8 shows the applicable page from the RS Components button reference documents.

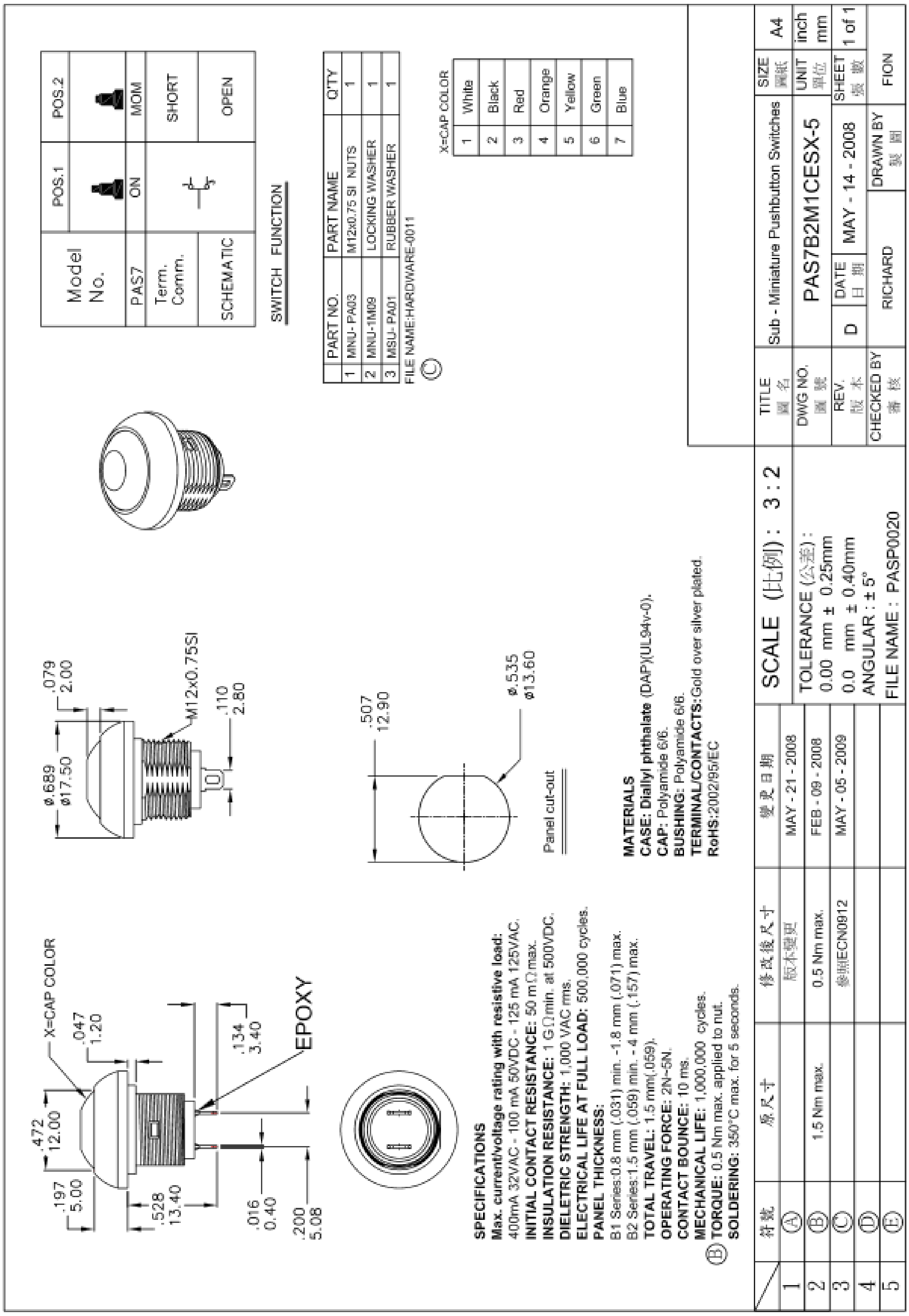


Figure F.8: RS Components button datasheet (RS Components, 2008)

Figure F.9 shows the applicable page from the JKL Components reference documents.

TYPICAL ELECTRICAL & OPTICAL OPERATING CHARACTERISTICS

(Ta = 25 degree C)

PART NUMBER	EMITTING COLOR	AMPERAGE mA	VOLTAGE Vdc	LUMENS	COLOR COORDINATES
LE-0603-04R	RED	12mA	24.0	2.00	630nm
LE-0603-04Y	YELLOW	12mA	24.0	2.00	595nm
LE-0603-04G	GREEN	12mA	24.0	9.00	525nm
LE-0603-04B	BLUE	12mA	24.0	2.00	470nm
LE-0603-04W	WHITE	12mA	24.0	10.00	x = 0.29 y = 0.28

REV. NO.	DESCRIPTION/ECO NUMBER	APPV'D DATE
G	CHANGE DIA. TO 10.5 MAX.	11/10/09
F	CHANGE mA FROM 20 TO 12	10/29/09
E	CHANGE MOL FROM 42.0 MAX. TO 43.0 MAX.	1/22/09
D	CHANGE CHARTS ADD NOTES	8/25/08
C	ADD ELECT & OPTICAL INFO	3/9/07
B	ADD + MARKING-24V DC	10/3/06
A	CHNG. 04B MSCP TO .14	7/24/06
	ENGR. RELEASE & CANCEL PL-0603-04-1 TO -5	7/5/06

METRIC

THIRD ANGLE PROJECTION

DIMENSIONS ARE IN MILLIMETERS

TOLERANCE UNLESS OTHERWISE SPECIFIED
1 PL +/- 0.2
2 PL +/- 0
ANGLE +/- 0

JKL COMPONENTS CORPORATION

TITLE: LED FESTOON LAMP

DRAWN BY: L. WENGSTROM | APPV'D BY: L.R. | DATE: 11/10/09

SIZE: A | FSCM NO. 55335 | DRAWING NO. LE-0603-04

- CAD DRAWING -
MANUAL REVISIONS NOT PERMITTED

SCALE: NONE | RELEASED DATE: 7/5/06 | REVISION DATE: 11/10/09 | REV. NO. G | SHEET 1 OF 1

Figure F.9: JKL Components LED datasheet (JKL Components, 2009)

Appendix G

Letter of Reference

Figure G.1 is a copy of a reference letter written by Johan Vermeulen, at the time, the Manufacturing Engineering Manager for GMSA.

GM South Africa

General Motors South Africa (Pty) Ltd
Reg No 1926/002852/07
Kempston Road, Sidwell
Port Elizabeth, 6001
P.O. Box 1137
Port Elizabeth 6000
Republic of South Africa
Tel +27 41 403 9111
Fax +27 41 403 2937
www.gmsa.com

06 March 2013

General Motors South Africa NMMU Chair of Mechatronics AGC Project

General Motors South Africa staff identified the need for automated transporters to assist in its efficiency improvement program and started investigating the various options available. The use of Automated Guided Vehicles(AGV), or its less complicated variant, the Automated Guided Cart (AGC) is an existing method that exists overseas and was identified as a potential solution where the transport of materials over short distances was not suited to a tugger driven vehicle as these are typical larger.

The use of these AGC's and existing technology available in this field are typically cost prohibitive in South Africa. The solutions available needs to be imported and are very complex and expensive. Simpler solutions have recently become available in South Africa, but it is still too expensive. In some of the Vehicle Assembly Plants in the east some very simple AGC's do duty but they are built in-house by the company and not commercially available. The designs are also not available as the plants were competitor plants.

This was then identified as an ideal project for a Masters student as part of the GMSA Chair of Mechatronics collaboration. The brief was to design, build and demonstrate a simple and lightweight AGC that is assembled from locally available components. It needed to be low cost with the cost of the prototype being substantially cheaper than recent locally available solutions. Gareth Cawood was assigned this task around March 2012 and within the 2012 Calendar Year managed to produce a working prototype that was small and simple, using regularly available components with the cost of all components coming in around 20-30% of the cost of a commercially available similar type of device.

The end product fulfilled the brief of being simple with no unnecessary features, therefore making it much more reliable and maintainable with no unnecessary cost built into it.
The product was demonstrated successfully and could complete a few cycles with the originally identified +-250kg trolley in tow.

We are very excited about the progress and believe that the work that Gareth had done forms an excellent base for developing the concept into a reliable, cost effective, flexible automated cart with multiple uses and in its execution realising savings for GMSA in terms of production efficiency.

Johan Vermeulen
Manufacturing Engineering Manager
GM South Africa

Figure G.1: GMSA Reference Letter

Appendix H

CD Contents

An attached CD contains the following data. Should the data on the CD not be available, the author can be contacted at gareth@gcawood.com to request below listed files.

H.1 Source Code

All software that was developed can be found here. For explanations of each file refer to section 4.4.

H.1.1 Python

H.1.2 PHP

H.1.3 Twido - PLC

H.1.4 Arduino

H.1.5 Software

Installation files for the following software required for the project:

- Python 2.7 Win 32bit
- Python SQl
- Python Serial
- Twido firmware
- WAMP
- Arduino programming Environment

The TwidoSuite installer could not be included due to its size exceeding that available on the CD.

H.2 Drawings for Manufacture of Prototype

PDF copies of all the files that were used in the manufacture of the AGC prototype.

H.3 Video Footage

H.3.1 Demonstration Video for SA Automotive Week

This video was used as a promotional video at the SAAW 2012. It contains video footage from testing which took place at GMSA's Struandale plant. At this stage the AGC was running at full speed and the track included the return loop.

H.3.2 Final testing video footage

The footage in this video was taken during final testing at the new NMMU Engineering building. The AGC can be seen to be travelling slower than in the previous video and the route is an oval shape.

This video also includes demonstrations of the emergency stop buttons, the bumper and IR proxi-sensor as well as remote control.

H.4 Thesis - PDF

A soft copy of the final thesis handed in for assessment.

H.5 Reference Documents

This folder contains many of the documents used during the project, of specific importance were the data sheets of various components.