The Research and Design of a New ABS System for Automotive by using the GMR Sensor

MSc by research Project

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Abstract

This dissertation explores the potential improvement of ABS design through the replacement of widely used Hall-effect sensor with the more sensitive GMR sensor technology and the replacement of wired with wireless transmission of information. The dissertation contributes an overview of main existing types of sensors that can be used for ABS design, describing the underlying technology of each as well as their main strengths and weaknesses. In addition, the dissertation proposes a GMR ABS design and reports on the results obtained during its validation through simulation and subsequent evaluation of a laboratory prototype built according to the design.

The contribution of this dissertation is threefold: the overview of existing sensor technology offers a comprehensive big picture of the field and serves to identify the most promising technology that can improve the performance of modern ABS; the design validated, implemented and evaluated provides conclusive proof of the feasibility of using GMR sensors and wireless transmission, as well as promising results regarding the potential performance gain; a comparison of the observed characteristics of the GMR sensor's performance during evaluation with known characteristics of the more usual Hall-effect sensor gives further evidence as to the potential gains that can be expected from a replacement of Hall-effect sensors with GMR sensors.

The results of this work represent initial proofs of concept

and of potential gains, opening thus a multitude of directions for future research, as detailed in the last chapter of this dissertation.

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Chapter 1 Introduction

Cars and transportation are an important part of modern life. As the number of cars on the road increases, traffic conditions become more and more complex (Wilschut and de Waard, 2011). In turn, this leads to an increased number of accidents, with an estimated number of 50,000 people killed in traffic every year in Europe alone (Brookhuis and de Waard, 2007). Most often, the causes of accidents are human errors that are increasingly due to the complexity of traffic conditions and modern driving (Smiley and Brookhuis, 1987; Brookhuis and de Waard, 2010). Consequently, the improvement of driver assistance systems is crucial in order to reduce the number of accidents and to increase safety for both drivers and passengers.

One of the driver assistance systems that are nowadays standard features of most modern vehicles is the ABS (Anti-lock Breaking System). The purpose of the ABS is to assist the driver during situations when intense or unexpected breaking is needed. During such situations, the vehicle may become unstable and/or less controllable as the skidding phenomenon occurs. Skidding is defined as an “unwanted sideways movement” (Gunsaulus, 1952, cited in Savaresi and Tanelli, 2010, on page 5) of the vehicle and is due to the fact that breaking normally causes a simultaneous decrease in the tyre's grip on the road and a significant increase of sideways forces that are applied to the vehicle (Savaresi and Tanelli, 2010). Thus, to ensure safety on the road, it is essential to minimise skidding while maintaining or even increasing the effectiveness of breaking. This is exactly what the ABS aims for (Savaresi and Tanelli, 2010).

The first version of ABS for cars was developed in the early 1900s and it was essentially an adaptation of a system previously used for trains (Savaresi and Tanelli, 2010). However, that initial version was quite different from current ABS, and it offered little improvement of the overall driving experience. Even as late as the 1960s, the ABS offered on top-end cars from known brands such as Chrysler or Cadillac actually increased safety at the expense of an increase in stopping distance (Savaresi and Tanelli, 2010). Since then, however, gradually, the car ABS evolved and diversified in terms of both overall performance and underlying technology.

A modern ABS is a quite complex system. Three of its main components that have a significant impact on the overall performance are the actuators, sensors and control algorithms. Most current ABS versions use hydraulic actuators to transmit the driver's pressure on the brake pedal to a hydraulic system that can then react appropriately to increase, decrease or maintain the brake pressure that is ultimately communicated to the brake discs of the vehicle (Savaresi and Tanelli, 2010). However, to transform the physical pressure on the brake pedal to final action of the system, another component is needed, namely the sensor.

Sensors used in modern ABS can be of various types. The choice of sensor type however is crucial for the overall performance of the resulting ABS, as each sensor type has its own strengths and drawbacks. An overview of current sensor types and their use in this domain reveals that rotational motion sensors are the most commonly used (Fleming, 2001). However, even considering only rotational motion sensors, there are still at least six different types of sensors that can be chosen when designing an ABS: variable reluctance sensors, Wiegand effect sensors, Hall effect sensors, magnetoresistor sensors, AMR magnetoresistive sensors and GMR magnetoresistive sensors.

Most modern ABS in the automotive industry use Hall effect sensors. This is mainly due to the Hall effect technology being relatively mature and reliable. However, newer technologies such as GMR magnetoresistive sensors could potentially bring additional benefits and further improve the performance of ABS that uses them. Nevertheless, as a change of sensor type triggers a change in the control algorithms of the ABS and potentially in its whole overall design, it is important to properly evaluate the potential benefits of a GMR sensor ABS over the prevailing version of Hall sensor ABS. This is precisely what this dissertation sets out to do, by designing, testing and evaluating the performance of a novel ABS that uses GMR sensors. The following sections of this chapter describe in more detail the aims and objectives of this dissertation, the methodology and the overall structure of the rest of this dissertation.

1.1 Aim and Objectives

The overall aim of this dissertation is to explore and evaluate the potential improvement that can be obtained by using GMR sensors for ABS in the automotive industry. The underlying hypothesis is that the high sensitivity of GMR sensors can be useful to improve the overall sensitivity of an ABS system that uses GMR. In addition, it is expected that the use of GMR sensors in ABS will likely improve the observed stability of the vehicle as well.

To achieve the above overall aim, the following more detailed objectives are defined and pursued:

1. Overview of existing types of sensors that can be used for ABS in the automotive industry, focusing on their strengths and weaknesses, in order to evaluate the potential benefits that can be gained through their use for new versions of ABS.
2. Design, implementation and verification of a novel ABS that uses GMR sensors.
3. Evaluation of the performance of proposed GMR ABS design, comparing it with the known performance of existing Hall ABS designs.

1.2 Methodology

The methodology for the first objective is mainly a literature review of relevant scientific articles, performance reports and other sources that offer information and data with respect to both the functioning and observed results of various types of sensors that can be used in ABS designs. The purpose of this literature review is to offer a clear picture of the main known strengths and weaknesses of the different types of sensors, in order to allow an initial informed prediction as to the type and significance of potential improvement to be expected from the use of each type of sensor and in particular from the use of GMR sensors in ABS.

After this literature review, an iterative and experimental approach is taken to design, build and verify a new ABS design that uses GMR sensors. This involves both computer simulations and builds of an ABS prototype system based on the design proposed. The main purpose of this step is to ensure that the novel design proposed is correct from a theoretical perspective, but also fully feasible in practice.

Finally, for the evaluation of the proposed design's performance, an empirical, experimental approach is taken. This consists in an experimental setup that allows the measurement of various performance characteristics of the proposed design, followed by the comparison of the measurements obtained with known performance measurements of existing Hall ABS designs.

1.3 Structure of the Dissertation

This dissertation is structured in six main chapters with their corresponding sections and subsections.

The current chapter is the first one, providing an introduction to the topic of the dissertation and a clear description of the aims and objectives, the methodology and the overall structure of the whole dissertation. The initial introduction gives an overview of the importance of driver assistance systems in general and the ABS in particular for ensuring safety in current traffic conditions. In addition, the introduction briefly describes the main components of the ABS, underlining the reasons why the choice and characteristics of sensors in an ABS are extremely important for its overall performance.

The next chapter gives an overview of existing advances in brake systems, focusing on the different types of sensors for ABS and their respective strengths of weaknesses. This chapter is essentially a literature review on the topic of sensors that can be used for the design of ABS.

The third chapter describes the novel GMR ABS system proposed by this dissertation. It gives an overall description of its aim and motivation, a detailed presentation of its design and components, as well as a validation of the design with the help of laboratory simulations.

The fourth chapter presents and discusses an evaluation of performance of the proposed GMR ABS system, by comparing it with known characteristics of the commonly used Hall ABS. In particular, the focus of this chapter is on the sensitivity observed for the GMR sensor during the practical evaluation and how it compares with the known sensitivity of standard Hall-effect sensors.

The fifth chapter describes the main limitations of the project presented in this dissertation, discussing also the implications of these limitations on the results and conclusions obtained.

Finally, the sixth chapter draws the overall conclusions of this dissertation and describes the directions that emerge as future work based on the results and investigations carried out as part of this dissertation.

Chapter 2 Brake System

Braking is an essential functionality of any car, allowing the driver to control the speed under any circumstances. This is particularly important in modern driving conditions that involve elevated driving speeds and complex traffic situations. However, the degree of control over speed that the driver obtains through the use of breaking depends heavily on the performance of the brake system of the car. This performance depends ultimately on the underlying technology and design of each particular brake system. Consequently, this chapter provides an overview of the evolution of brake systems in terms of underlying technology and designs, as well as a more detailed presentation of the main components of current brake systems (ABS) and the types of sensors that they use.

2.1 Evolution of brake systems technology and design

Modern brake systems are the result of successive improvements of previous brake systems, most often achieved by taking advantage of new technology or materials. To fully understand current brake systems and how they can be best improved, it is helpful to briefly review first the main technological advances that were used in the past to improve the performance of brake systems up to what we now take for granted.

The main principle of brake system remained remarkably unchanged over the years: friction is used as a means to slow wheel movement as desired (2CarPros, n.d.) However, the way in which additional friction is induced and controlled has changed significantly. Initial brake systems used before the 1920s were mechanically operated: rods or cables served to directly transform the pressing of the brake pedal into a pushing of some form of “brake shoes” or their equivalent against the wheel drum (Mavrigian and Carley, 1998). Moreover, at that time, most vehicles had brakes only on the rear wheels, given that four wheel mechanical braking required a complex system of rods and cables to ensure the stability of the vehicle (Mavrigian and Carley, 1998).

The first technological breakthrough to significantly change brake systems was the invention of hydraulic brakes in 1918 (Mavrigian and Carley, 1998). Hydraulic brakes replaced the rods and cables of mechanical brakes with pistons applying the brake force to fluids that would, in turn, transmit this force to the pistons of each wheel brake. A depiction of a hydraulic brake system is shown in Figure 1.

Hydraulic brakes brought two extremely significant advantages: first, the brake force was distributed equally to the wheels, without the need for complex, additional balancing systems; second, the force applied to the pedal was magnified as it was transmitted to the wheels, making it much easier to stop a vehicle or even slow it down. Combined, these two advantages greatly increased the safety as vehicles as four-wheel braking became the norm rather than the exception and braking simply became easier and more effective (Mavrigian and Carley, 1998).

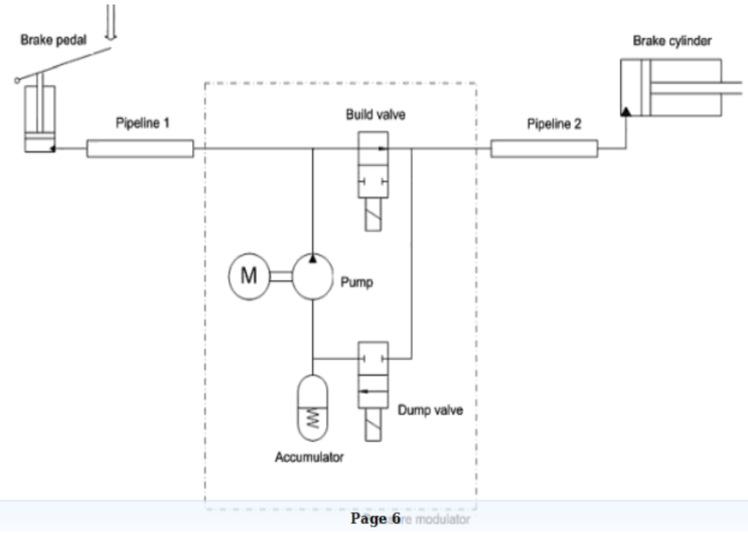


Figure 2: Depiction of a hydraulic brake system (adapted from Savaresi and Tanelli, 2010)

Ten years after the invention of hydraulic brakes, another technological breakthrough greatly improved brake systems: vacuum boosters were added to brakes, transforming them in the so-called power brakes (Mavrigian and Carley, 1998). Over the next years there were several changes and improvements to power brakes, but a modern version of the original power brakes are still used on most light trucks and other vehicles (Mavrigian and Carley, 1998).

Although it took longer for the next technological breakthrough to change the design of brake systems, it happened nevertheless. Starting with the 1950s, drum brakes were gradually replaced by disc brakes. The main advantages of discs over drums were that they were easier to cool down, lighter, self-adjusting and more robust (Mavrigian and Carley, 1998). However, disc brakes are also more expensive and it's for this reason that drum brakes are still used even today although mainly for the rear wheels of vehicles (Mavrigian and Carley, 1998).

Finally, the latest major improvement in brake systems was the invention of the electronic ABS. Unlike previous advancements, the ABS did not as much change the basic functioning of a brake system as it added new functionality to make it more reliable, safer and easier to use. The main purpose of the ABS is to avoid skidding and locking of the wheels during braking (Savaresi and Tanelli, 2010; Mavrigian and Carley, 1998). In turn, this increases vehicle stability during braking and enables the driver to maintain control over steering even during emergency braking and other potentially dangerous situations. Currently, the electronic ABS is a standard option on most of the vehicles that are produced (Mavrigian and Carley, 1998).

2.2 *ABS functioning*

The overall diagram of an ABS system in a car is shown in Figure 2. As it can be noted from the figure, the actual antilock brake is only part of the system, with additional speed sensors on the wheels, an ABS computer and a simple warning light that gives an ABS warning to the driver.

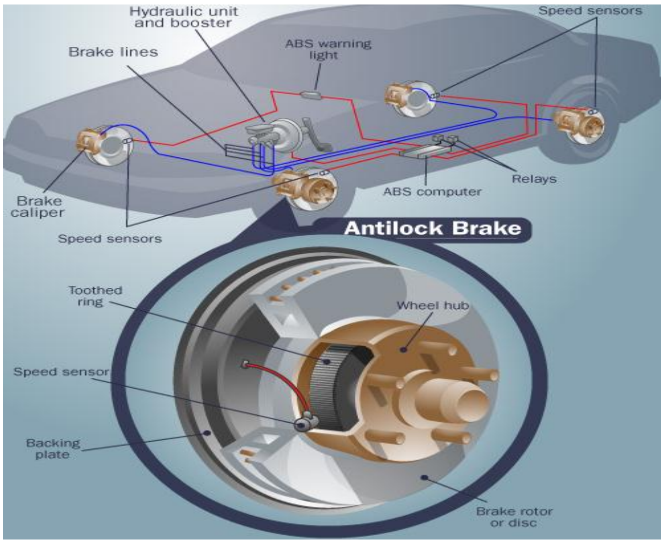


Figure 3: Overall diagram of an ABS system in a car (adapted from Nice, 2000)

An ABS consists of three main parts: actuators, sensors and a controller system (Savaresi and Tanelli, 2010). Actuators transmit the driver's pressure on the brake pedal to the braking system. Sensors essentially collect information that the controller needs in order to detect potentially dangerous situations in which the ABS can help stabilise the vehicle and avoid skidding.

Finally, the controller basically decides on both when and how to use the features of the ABS as a whole in order to best assist the driver.

In modern versions of ABS, the actuators are usually hydraulic systems such as the one depicted in Figure 1. Essentially, such an activator consists in two valves, a pump and accumulator (Nice, 2000). The valves are controlled by the controller, which can use them, on most systems, to either increase, decrease or maintain constant the braking pressure (Savaresi and Tanelli, 2010). Hydraulic actuators are currently preferred and used in most ABS systems because they are highly reliable and have a long life cycle (Savaresi and Tanelli, 2010). However, they also have one potential disadvantage: they are essentially wired to the brake pedal and thus “the driver feels pressure vibrations on the brake pedal when the ABS is activated” (Savaresi and Tanelli, 2010, p. 7).

Although all three components of an ABS are important for its final performance, actuators can play a special role as the ABS' controller basically relies on their accuracy and adequacy to decide on what corrective actions to take at any given moment. Depending on the type of information that they collect, usual types of sensors include rotational motion sensors, pressure sensors, angular and linear position sensors, as well as temperature sensors (Fleming, 2001). The most commonly used types of sensors for ABS systems are the rotational motion sensors (Fleming, 2001), as they detect the type of rotational motion that the wheel is expected to have when no skidding occurs.

In addition to the different types of information that sensors can be meant to collect, there are also different technological approaches that can be used to build a sensor. Rotational motion sensors for instance can be built using variable reluctance, the Wiegand effect, the Hall effect, magnetoresistors, AMR magnetoresistance or GMR magnetoresistance (Flemming, 2001).

2.3 *Most common types of sensors*

As mentioned previously, there are different types of sensors that can be used to collect the information required by the controller of an ABS system. This section briefly describes the most used types of sensors and their respective advantages and disadvantages.

2.3.1 *Variable reluctance sensors*

Variable reluctance sensors essentially consist in a magnetic circuit and a sensing coil that is used to measure the flux variations as reflected in the voltage variations induced according to Faraday's law by the rotation of the gear (Flemming, 2001). Consequently, such sensors are quite simple and therefore cheap to produce. Other advantages include their small size and stable performance even in conditions of varying temperature (Flemming, 2001). However, their performance is relatively limited as they do not offer any information for instance at zero speed and, moreover, the information they provide depends essentially on the speed of rotation of the gear (Pawlak, Adams and Shirai, 1991; Flemming, 2001).

2.3.2 *Wiegand effect sensors*

Wiegand effect sensors can be considered as a first improvement over the basic variable reluctance sensors described in the previous section. Such sensors use a magnetic sensor that generates a voltage pulse whenever the strength of the induced field surpasses a given threshold (Flemming, 2001). Consequently, unlike simple variable reluctance sensors, Wiegand effect sensors can offer more information even at low speeds. However, they are more expensive to build and use (Flemming, 2001).

2.3.3 *Hall Effect sensors*

Hall effect sensors are the most commonly used types of sensors in current standard ABS. Compared to Wiegand effect sensors, Hall effect sensors are more sensitive and their output is more easily used for ABS controlling purpose. Essentially, rather than detecting only fluctuations of the induced field above the set threshold level, Hall effect sensors map all fluctuations of the magnetic flux that are generated by the rotation of the gear (Hall, 1879; Flemming, 2001).

Hall effect sensors rely on the Hall coefficient to measure directly the induced flux level (rather than the time-derivative of the flux, as measured by simple variable reluctance sensors). An important advantage of Hall effect sensors is that they “are made using bipolar semiconductor technology which allows their fabrication directly on the same chip along with microelectronic signal-processing circuitry” (Flemming, 2001, p. 300). This results in a cheap fabrication cost and small final size. In addition, their detection of each fluctuation of the induced flux offers the benefits of providing detailed information even at zero speed and a linear signal that can thus be easily used by the controller for accurate decisions. Moreover, Hall effect sensors tend to be quite robust as they are normally not affected by dust, dirt, mud or water. However, they can be sensitive to interference from other magnetic fluxes and their output normally has to be amplified by a transistor-based circuit in order to be in the range of values normally used by drive actuators.

2.3.4 *Magnetoresistor sensors*

Magnetoresistor sensors use a slightly different approach compared to the previous three types of sensors: they also measure basically the flux generated by the rotation of the gear, but they do this by changing their resistance proportional to the change of magnetic flux density. From a technical point of view, this is achieved by using particles of semiconductors that are placed in thin layers on specially designed paths: depending on the magnetic flux density, the conduction current will take a path with higher or lower resistance (Partin et al., 1999; Fleming, 2001).

Similarly to Hall effect sensors, magnetoresistor sensors have the advantage of relatively low cost as they can be produced using integrated circuits on a chip. Moreover, magnetoresistor sensors also continue to collect reliable information even at zero speed or in conditions of variable temperature and they also give information about the direction of the rotation (Fleming, 2001). However, potential disadvantages of this type of sensors are the relatively larger size compared to Hall effect sensor and their bias current requirement (Fleming, 2001).

2.3.5 *AMR Sensors*

AMR stands for anisotropic magnetoresistive. Unlike previously discussed sensors, AMR sensors measure primarily changes of orientation and/or direction of the magnetic field rather than variations of its density. An AMR sensor usually consists in a configuration of four distinct sensor elements, each of them having a thin layer of special magnetised permalloy that essentially react to changes of orientation/direction of the magnetic field by changing resistance (Caruso et al., 1998). Overall, AMR sensors share the same general advantages and disadvantages of generic magnetoresistor sensors.

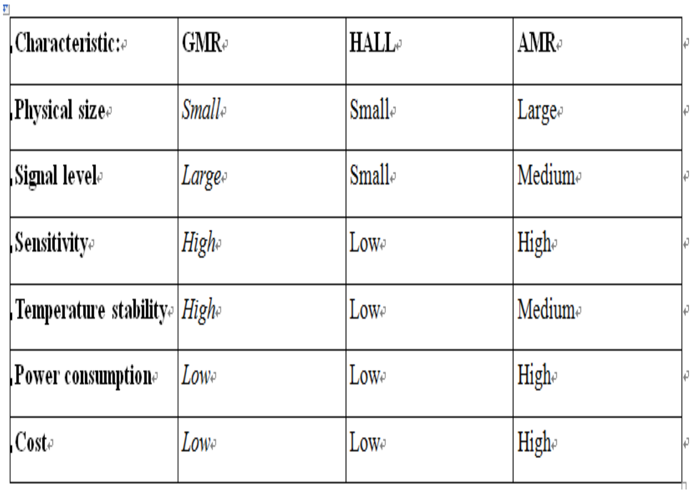
2.3.6 *GMR Sensors*

GMR stands for giant magnetoresistive. Despite their name, they are not in fact significantly larger in size than other sensors, but they simply have an increased sensitivity to the variation of the magnetic field. Similarly to AMR sensors, GMR sensors also react to changes of direction/orientation of the field, but they do so to a higher degree. This is essentially due to the difference of the underlying operating mechanism: GMR sensors rely on the GMR effect, which is basically a quantum mechanics effect. A GMR sensor normally has several alternating thin layers of magnetic and non-magnetic material, which serve to allow the GMR effect. Depending on the orientation/direction of the magnetic field, the electron spin in those materials will be modulated and the resistance will also variate (Grunberg et al., 1986). The GMR effect consists in the fact that the resistance of successive magnetic layers changes according to the change of angles between magnetisation directions of successive layers (Coehoorn, 2003).

The actual performance of a GMR sensor depends on several aspects and, most notably, the characteristics of the material used in the layers. Most commonly used GMR sensors have a decrease in resistance between 14% and 16% (Grunberg et al., 1986).

The main advantages of GMR sensors are their increased sensitivity that allows for increased accuracy of measurement, their small size and increased robustness of operation in the presence of higher fields than those for which AMR or Hall sensors can be used. In addition, unlike Hall sensors whose operation depends on temperature, GMR sensors are temperature independent (Kapser, Zaruba, Slama and Katzmeier, 2008). However, GMR sensors also have a few disadvantages, most notably the relatively higher cost compared to other types of sensors and their bias current requirement (Fleming, 2001).

Summarising, the main characteristics of GMR, Hall and AMR sensors are shown and compared in Table 1. As it can be seen from the table, overall, GMR sensors offer clear advantages such as better sensitivity, temperature stability and signal level. Consequently, this dissertation will explore various ways to take advantage of those characteristics in order to improve ABS performance.



Characteristic:	GMR	HALL	AMR
Physical size	*Small*	Small	Large
Signal level	*Large*	Small	Medium
Sensitivity	*High*	Low	High
Temperature stability	*High*	Low	Medium
Power consumption	*Low*	Low	High
Cost	*Low*	Low	High

Table 1: Main advantages of GMR compared to the corresponding characteristics of Hall and AMR sensors (adapted from Kapser, Zaruba, Slama and Katzmaier, 2008)

Chapter 3 Proposed GMR ABS system

This chapter presents and describes the proposed design of the novel GMR ABS system. Section 3.1 below discusses the main aim and motivation of the design. Section 3.2 gives a high-level overview of the proposed system, followed by detailed presentation of each component and a discussion of the main design decisions taken as well as their rationale. Finally, section 3.3 discusses the steps taken to validate the proposed design and gives results of the validation tests.

3.1 *Aim and Motivation*

Based on the technical characteristics of the various types of sensors presented and discussed in the previous chapter, the main hypothesis of this dissertation is that the replacement of current Hall-effect sensors in ABS systems with higher-performance GMR sensors would result in better ABS systems that have essentially better sensitivity and can ensure better vehicle stability. In addition, a second hypothesis is that wireless communication of information from sensors to the central control unit is likely to offer better flexibility of the resulting ABS system at similar levels of performance with wired ABS systems. The design proposed in this chapter aims to provide the means of exploring and testing these hypotheses.

To achieve the overall aim of exploring and testing the above hypotheses, the proposed design focuses on the two main innovations that are investigated, namely the use of GMR sensors and wireless communication in an ABS. Thus, the purpose was not to build from scratch an entirely novel ABS, but simply to design a minimal lab prototype of a GMR ABS that uses wireless transmission of information from sensors to the central control unit. The aim of designing and building such a lab prototype is threefold: first, it serves to assess the feasibility of using GMR sensors and wireless communication in an ABS; second, it provides the opportunity to test the potential performance improvements that might be obtained by replacing Hall-effect sensors that are currently used in most ABS designs with GMR sensors and, respectively, wired communication with wireless communication between sensors and central control units; third, the lab prototype allows the exploration and identification of potential issues that might arise from the use of GMR sensors and wireless communication in ABS.

3.2 *General design and components*

The general design of the proposed GMR ABS follows as closely as possible standard designs of existing ABS. Therefore, the general, standard workflow of a braking system is preserved in the proposed design as well, as shown in Figure 3. Nevertheless, changes are made to the design and implementation of several components, namely the sensors, the control unit and the communication system between them, as discussed below.

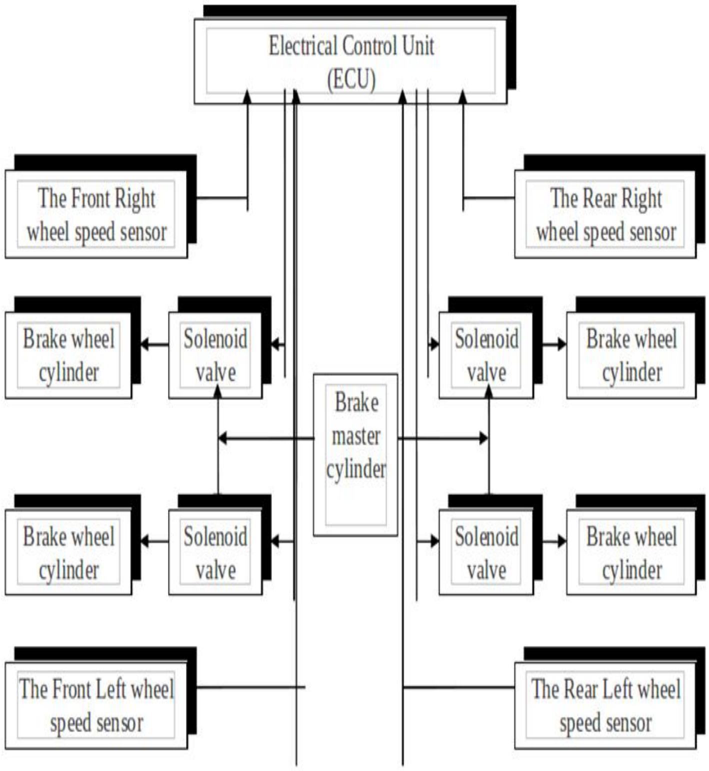


Figure 4: The general, standard workflow of a braking system,

preserved as such in the proposed design (adapted from Savaresi and Tanelli, 2010)

Given that the purpose of this new design is to explore the feasibility and potential performance gains of using GMR sensors and wireless communication, an initial design decision was to maintain as much as possible standard design features, changing only what was required in order to replace the usual Hall-effect sensors with GMR sensors and wired communication with wireless communication. Consequently, parts such as the solenoid valve or pump motor circuit design are the standard, usual ones, while the main innovations are present in the part of the design related to information collection from the wheels and its transmission to the central processing unit. This is reflected in Figure 4 below, which provides a high-level view of the main components that are changed and the way in which they interact.

As Figure 4 shows, the proposed design can be considered to have three main components: the GMR sensor, the wireless transmission system and the controller (or control unit). The following subsections describe in detail the design for each of those components and provide the rationale for the various design decisions that were taken.

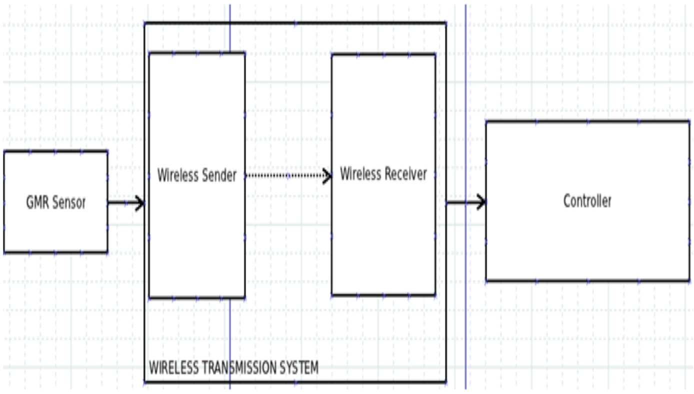


Figure 5: High-level overview of proposed GMR ABS system design, showing the three main components that are altered with respect to a standard design (adapted from Nice, 2000)

3.2.1 *GMR Sensor*

The first design decision to take was related to the best approach to take in order to find suitable GMR sensors for this project. There were two main choices: either to design and fabricate in the lab a GMR sensor, or to choose and buy a suitable sensor from the options already available on the market. Given the relatively large variety of GMR sensors available, the second option was preferred and an investigation was conducted to evaluate the characteristics of the different varieties of GMR sensors in order to find the best suitable one.

The investigation of existing GMR sensors focused on the performance and specific advantages offered by each type of sensor. In particular, the best performance was deemed to be that of biased GT sensors and the NVE's AKL001-12 model was found as an accessible model that implements this technology. A block diagram depicting the different parts of NVE's AKL sensor series is shown in Figure 5.

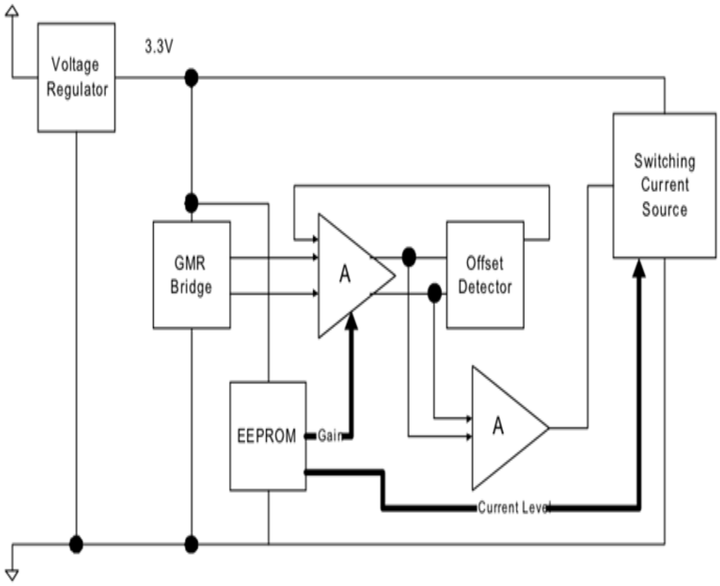


Figure 6: Block diagram of the AKL series sensor parts (adapted from NVE, 2003)

The AKL sensor series essentially provide a pulse output signal with the high value corresponding to a gear tooth passing in front of the sensor and a low value corresponding to the gear tooth moving away from the sensor. This results in a train of pulses that can be used to easily determine the speed of the gear. The difference between the various models in the AKL series consists in the different spacing of elements, ranging from 1000 microns for the AKL001-12 to 300 microns for the AKL003-12. In turn, this determines the pitch range of gear teeth for which the sensor can be used. Due to the characteristics of the gear wheel used for testing (as described in chapter 4), the AKL001-12 model was chosen, as it is useful for a pitch of 2.5 to 6mm (NVE, 2003).

The main advantages of the chosen type of sensor and in particular of the AKL001-12 model are the following (NVE, 2003):

1. Frequency of output signal that is proportional to the speed of the rotating wheel.

2. Up to 10kHz frequency response, corresponding thus to the speed of 500km/h.

3. Effective protection against electromagnetic

interference from other sources.

4. Maximum air gap of 6mm.

5. 50% duty cycle.

6. Zero speed operation.

7. Precise spacing between sensor elements.

8. Excellent temperature and voltage performance.

9. Small, low profile surface mount package.

Despite the above advantages, the chosen sensor also has several disadvantages: sensitivity to the position of the magnet with respect to the sensor, sensitivity to mechanical imperfections on the surface of cheap magnets, sensitivity to high temperature of the environment (NVE, 2003). Consequently, the next design decision was to use this type of sensor in a head array configuration using the three-channel method, in order to mitigate the potential negative impact of these drawbacks.

The head array configuration consists of four GMR sensors heads (including each a permanent magnet and the corresponding GMR components) that allow thus the data to be collected at four different points. In turn, this means that each change of the gear position would result in four different signals being provided by the sensor array, which allows the correction of any bias or instability caused by the potential wobble of the gear or a change in the position of the magnet with respect to that of a sensor. However, in order to make such correction, the design of the control unit had to be changed accordingly. More details on the design of the control unit are provided in subsection 3.2.3 below.

3.2.2 *Wireless Transmission System*

The wireless transmission system consists essentially of a wireless transmitter located by the sensors and a wireless receiver on the other side, by the control unit. The main rationale for exploring the switch from wired to wireless transmission in the ABS was that it increases the flexibility by allowing simple use of many different types of sensors, even simultaneously, as the signals from all sensors can be combined together for transmission and then separated for further processing and decision making by the control unit's processing circuits. Thus, the use of wireless transmission would enable new ABS systems that gather additional detailed information on a variety of aspects such as air pressure in the wheels, temperature, or distance. This kind of additional information can help the control unit to make better decisions that take into account all those aspects and thus improve the driving experience and safety at the same time.

In addition to the above, another important reason for exploring the use of wireless transmission in ABS is that current wireless technology offers good stability and a transmission speed comparable to that of a wired system. Consequently, there seem to be few drawbacks to the use of wireless, while the advantages could be significant.

For the best design, the choice was made to use the ER400TS-02 transmitter and its corresponding receiver ER400RS-02. The chosen transmitter and receiver are part of the ERx00-02 series provided by Low Power Radio Solutions (LPRS, 2005). They are very simple radio devices with a range of 250 metres (line of sight) and allowing the optimisation of frequency, data rate and power output to fit a particular use (LPRS, 2005). In addition, they are configurable to a certain extent by using the embedded software that is provided with them. The block diagrams are provided in Figure 6 and Figure 7 respectively, while the characteristics of these devices are the following (LPRS, 2005):

1. High sensitivity at the receiver, with the specification indicating 103dBm at 19.2Kbps
2. A maximum of 10mW transmit power at 434MHz.
3. Frequency accuracy ensured through the use of a crystal controlled synthesizer.
4. Low power consumption (between 21 and 25mA) and operating voltage (2.5-5.5V)
5. Software adjustable BAUD rate and channel frequencies
6. Configurable power settings for each channel
7. Software error checking and encryption possibility

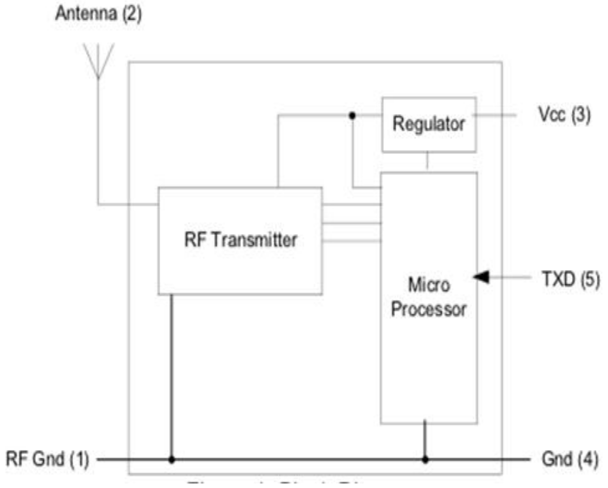


Figure 7: Block diagram of wireless transmitter from ER400TS-02, used in the proposed design (adapted from LPRS, 2005)

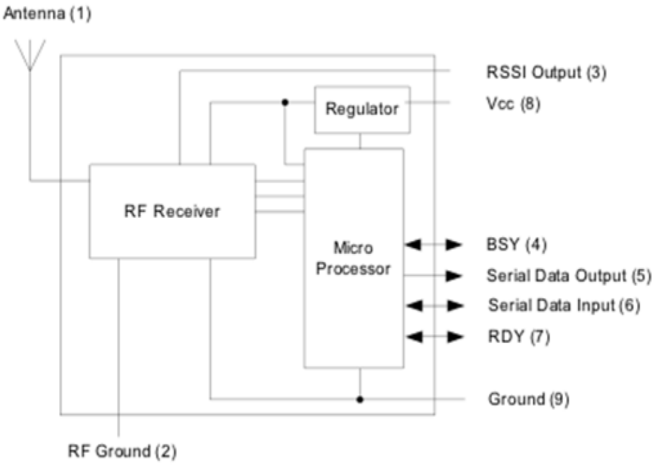


Figure 8: Block diagram of wireless receiver ER400RS-02, used in the proposed design (adapted from LPRS, 2005)

The above transmitter and receiver were chosen mainly for their simplicity, ease of use and flexibility of configuration. However, in order to integrate them into the proposed design, several parameters had to be set and the interfacing with the head array sensors had to be done.

The parameters to set for the wireless system were the following: data rate, transmitter and receiver frequency, output power. All parameters were set using the provided software located in the file ER V2_03.exe. The data rate was set to 19200 (ER_CMD U4 constant in the software), the frequencies were set to 434MHz (ER_CMD C7) and the output power was set to 10mW (ER_CMD P9).

In principle, the transmitter would be directly linked to the sensor, receiving thus the sensor's output and simply transmitting it further to the receiver. Similarly, the receiver would just get the transmitted signal and pass it to the central control unit. However, a direct connection between the array sensor configuration and the transmitter is neither possible nor entirely desirable. Consequently, the signals from the array sensor are first filtered through a voltage comparator and then processed by a specifically programmed microcontroller before being actually fed into the transmitter for wireless transmission. The role of each of those components is explained below.

The reason for using a voltage comparator to filter the direct output of a sensor array is to ensure that the signal is basically in the correct format and range accepted by the microcontroller. This means in particular that the analogue signal provided by the sensor is transformed into a digital signal with values chosen in the range of the microcontroller by comparison of the original signal to a reference voltage. The signal processing is done by using a high speed voltage comparator, namely the LM211 chip (Texas Instruments, 2004). The LM211 chip is chosen as it is a simple chip used for automotive applications, which satisfies the requirements of its intended use in this design: it operates within the ranges required by the sensor's output signal on one hand and the microcontroller's input range on the other. Thus, the LM211 is wired so that it collects the signal from the sensor on its port 3, compares it with the reference signal provided on port 2 and then it feeds the result to the MCU chip AT89C52. The signal processing circuit for LM211 is shown in Figure 8.

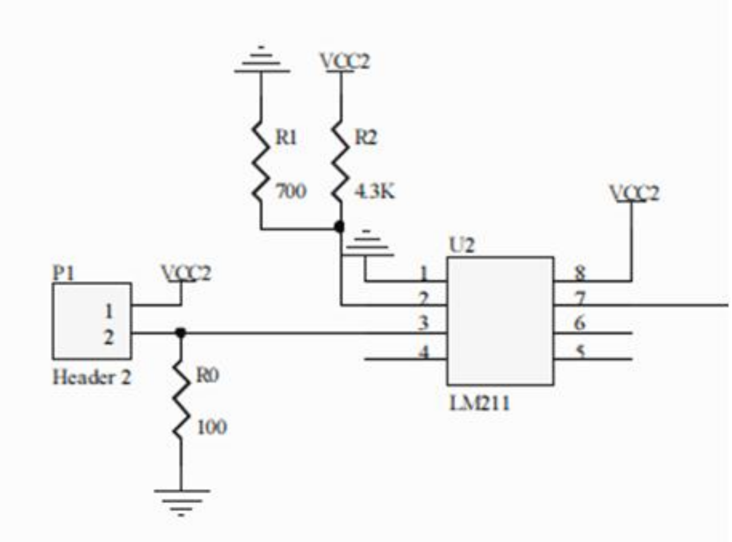


Figure 9: Processing circuit for signal comparison with LM211 chip, used in the proposed design (adapted from LPRS, 2005)

After the signal is processed by the LM211, it is fed into the MCU chip AT89C52. The purpose of this MCU is essentially to transform the signal into the TXD mode required by the wireless transmitter. Thus, the MCU is wired between the LM211 and the transmitter, as shown in Figure 9. Both the wireless receiver and wireless transmitter are shown in Figure 10.

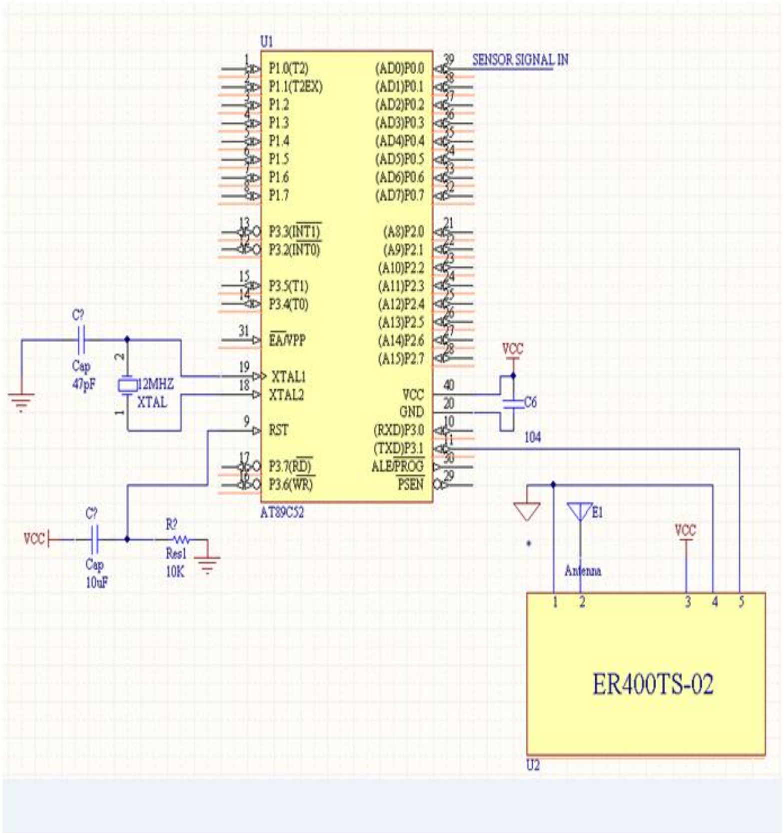


Figure 10: Partial circuit diagram showing the connection of the wireless transmitter to the MCU AT89C52 that transforms the signal into the TXD mode required for wireless transmission (adapted from LPRS, 2005)

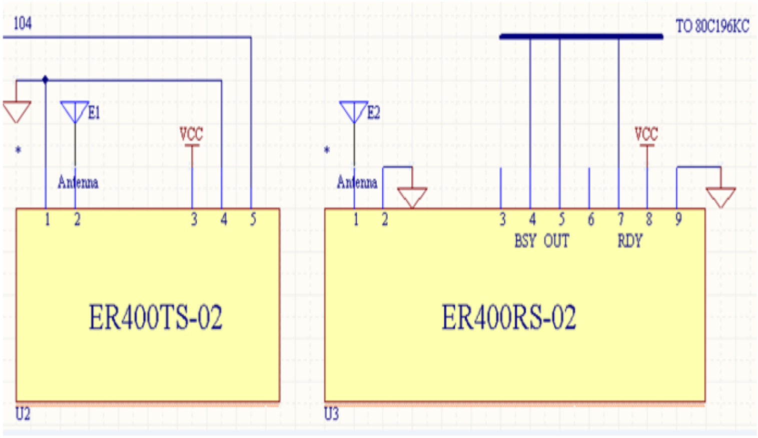
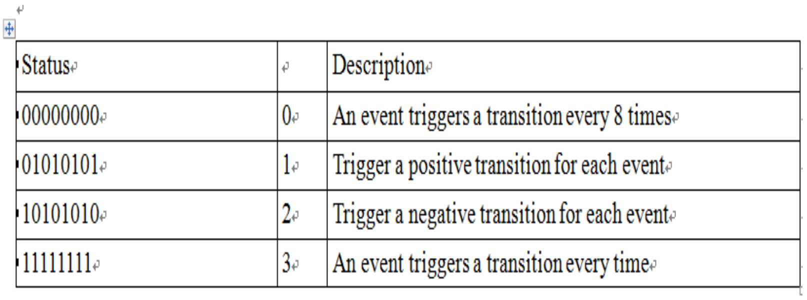


Figure 11: Partial circuit diagram, showing the wireless transmitter (receiving its input signal from the MCU AT89C52 on port 5) and wireless receiver (forwarding the signal to the 80C196KC control unit)

3.2.3 *Controller (Control Unit)*

The last main component of the proposed design is the main control unit represented by the Intel MCU 80C196KC chip. This chip was selected as it is commonly used for processing of wheel speed signal inputs. The Intel 80C196KC chip (Intel, 1991) is a 16-bit, high-performance microcontroller with four high-speed inputs (HSI), HSI0 to HSI3. The microcontroller also has the following features: HSI gating logic, eight divided counters, an input transition detector, FIFO interrupt and control logic, FIFO registers, HSI time to register, HSI way and HSI status registers' registers (Intel, 1991).

The high-speed input channels offer three special registers: HSI_STATUS, HSI_TIME and HSI_MODE. Depending on the values in those special registers, the high-speed input ports can be used to test whether the time occurs on the pin and to note the occurrence time. Moreover, the FIFO queue features allows the recording of up to 8 hours of data that can then be read and processed by the CPU in a timely manner, in order for the microcontroller to function properly even in environments with high speed acquisition of data. The meaning of the statuses of the four high-speed input channels is shown in Table 2.



Status		Description
00000000	0	An event triggers a transition every 8 times
01010101	1	Trigger a positive transition for each event
10101010	2	Trigger a negative transition for each event
11111111	3	An event triggers a transition every time

Table 2: The internal states of the four high-speed input channels in the MCU 80C196KC and their respective meaning (from the MCU 80C196KC datasheet)

To achieve the type of processing required by the proposed design, the MCU 80C196KC had to be programmed accordingly. For this, a decision had to be made first with respect to the programming language chosen for this task: either assembly language or C. Programming in assembly language is in general more tedious and results in larger, although potentially more efficient code. On the other hand, programming in C is faster, easier and tends to result in shorter code. Given that the programming was realised here for a prototype project, the C language was chosen to program the microcontroller, as the speed and facility of programming were more relevant for this type of project than a potential improvement of performance due to careful tuning of assembler code.

For the programming of the microcontroller, the standard Keil software (ARM, n.d.) suite was used. Keil is useful as it can simulate peripherals and thus it provides a virtual environment in which initial tests can be made quickly and efficiently. The overall workflow of the processing implemented for the MCU 80C196KC is shown in Figure 11. The implementation consists in eight distinct functions, as follows:

1. Main function (located in Main.c file)
2. ABS main function (located in ABS_main.c file)
3. Input and output port initialisation function (located in io.c)
4. GPT1 unit interrupt function (located in GPT1.c)
5. GPT2 unit interrupt function (located in GPT2.c)
6. CC1 wheel speed interrupt processing function (located in CC1.c)
7. CC2 wheel speed interrupt processing function (located in CC2.c)
8. Fast external interrupt initialisation function (located in int.c)

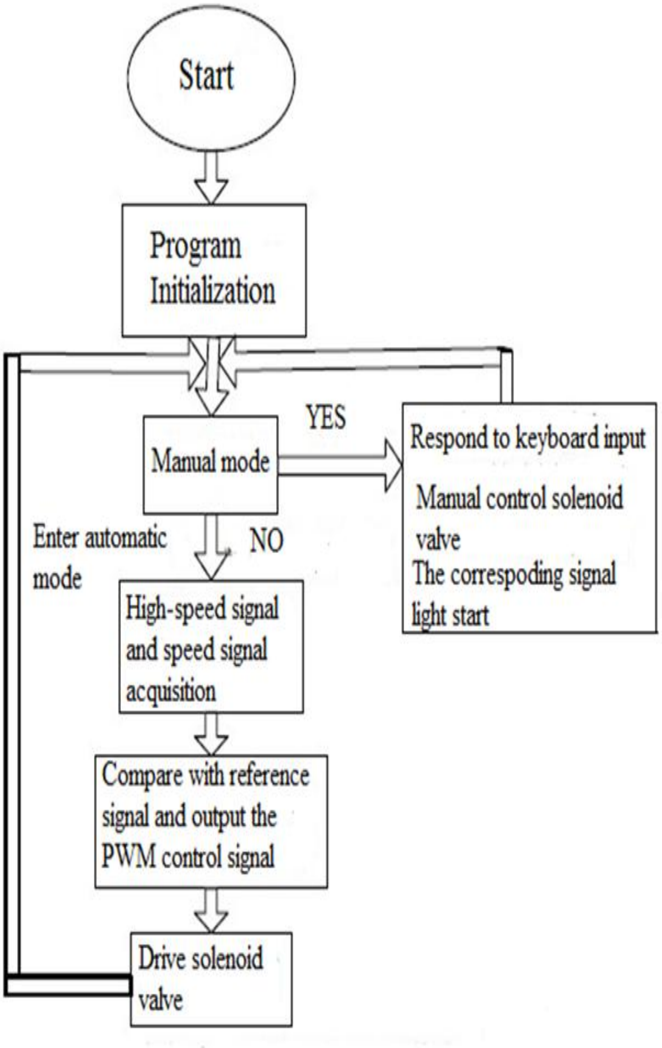


Figure 12: Flow chart showing the overall workflow implemented for the MCU 80C196KC (adapted from Keil 8051 Microcontroller Development Tools, 2012)

3.3 *Design validation*

The overall aim of design validation was to ensure that the proposed GMR ABS worked properly and behaved as expected. For this aim, a simulation environment was used as the cheapest and simplest solution available that was also entirely adequate. The system was split into its main component parts and the simulator was run for each of them, to ensure that the generated outputs corresponded to the expected ones, given the inputs provided. In particular, the following different parts were tested in a simulation environment: the MCU signal process circuit, the solenoid valve control circuit and the pump motor control circuit.

The following sections describe the choice of simulation environment as well as the simulation setup and results obtained for each of the three main parts of the proposed GMR ABS.

3.3.1 Simulation environment

For validating the proposed GMR ABS, the Protel 99 SE (Protel, 2001; Altium Ltd., 2001) circuit design and simulation software was chosen. The choice was motivated by the fact that Protel99SE fully supported the design and validation process from the first steps of building the needed circuits to the last steps of actually specifying inputs and testing various parts of the whole system as well as the system as a whole. In particular, the simulation environment offered a convenient way of simulating the design of the printed circuit board (PCB) in its entirety, ensuring signal integrity as well as electrical connectivity throughout. In turn, this meant a higher confidence in the simulation results as correct indicators of the validity of the GRM ABS design, since the implementation afterwards in a prototype was straightforward.

Additional characteristics of Protel 99 SE that make it an adequate choice for design validation of the proposed GMR ABS are the following: convenient access to the complete set of tools that were needed for both design and validation phases, including for instance the schematic editor, mixed-signal circuit simulator and Signal Integrity Analysis tool (Altium Ltd., 2001); design database allowing easy storage and access of different versions of the design as well as its component parts (Altium Ltd., 2001); comprehensive and up-to-date component libraries containing all the required component for the proposed GRM ABS.

3.3.2 Simulation of MCU signal process circuit

The diagram of the MCU signal process circuit is shown in Figure 12, using the exact components previously described in the overall system's design. As detailed in the presentation of the system's design, the MCU signal process circuit includes all the components required to collect the information from the sensor array, filter it and transform it to the right format for further processing, transmit it in a wireless manner to the MCU and finally make decisions based on it, according to the logic coded into the MCU 80C196KC.

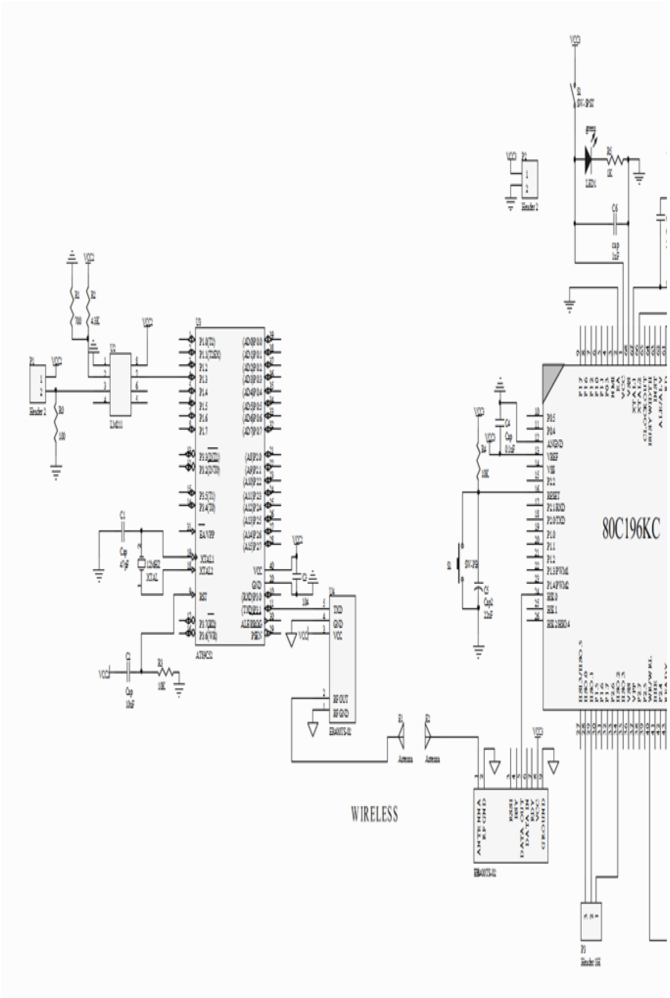


Figure 13: Diagram of MCU signal process circuit (From Altium Designer Schematic, 2001)

The main aim of the simulation for this part of the system was to ensure that the signal from the sensor array is properly collected, treated for noise filtering and format transformation, as well as successfully transmitted through the wireless systems. Consequently, the following simulation was designed and carried out: an input signal corresponding to the sensor's output is applied and the resulting signal is then visualised at the various significant points of the circuit. The values used and results obtained are detailed below.

To simulate the sensor's activity, an input signal generator is used, providing a peak to peak 5V sine signal, as shown in the image of the first oscilloscope XSC1 in Figure 13. This corresponds directly to what the sensor array is expected to provide when the wheel is moving. The actual frequency of the sine signal corresponds to the speed of the wheel. However, the actual functioning of the sensor itself could not be tested through the simulation and is tested instead directly on the lab prototype of the system, described in the evaluation section 3.4 below. During this simulation, the sensor output is considered to correctly represent the wheel's actual movement and the focus is instead on ensuring that successive transformations of this signal are correct.

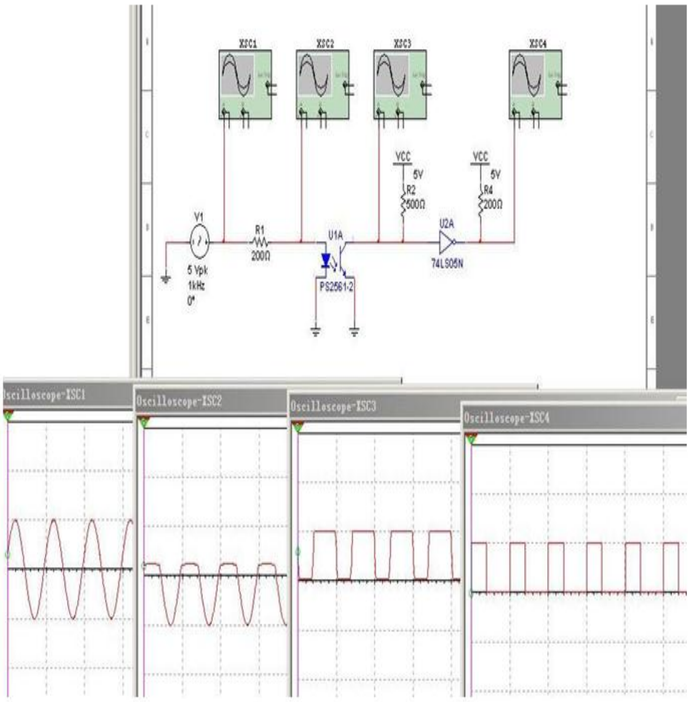


Figure 14: Simulation settings and results for the MCU signal circuit (From Altium Designer Schematic, 2001)

The first transformation to check is the noise filtering of the signal and its transformation to the range accepted by the MCU. This is basically done through comparison with a reference signal and the result is shown in the image of the second oscilloscope, XSC2, in Figure 13 above. Finally, the signal is filtered and transformed to a regular square waveform that is accepted as input by the MCU, as shown in the remaining oscilloscope images in Figure 13.

3.3.3 Simulation of the solenoid valve control circuit

The simulation of this part of the system was mainly done to ensure the compatibility with the chosen MCU design, as well as the correct implementation of this part of the circuit. An important issue was to ensure that the signal obtained was strong enough to properly drive the solenoid valve. Consequently, the test consisted in simulating the path of the signal from the MCU through a hex inverter and an opto-transistor to the solenoid valve, as shown in the circuit diagram in Figure 14, and measuring the current obtained, comparing it with the required range specified in the valve's datasheet. For the purpose of the simulation, the solenoid valve's coil was simulated using a resistor. The corresponding simulation setup and results are shown in Figure 15. As it can be seen from the measurements in the figure, the current obtained is strong enough to drive the solenoid valve properly, according to its specification.

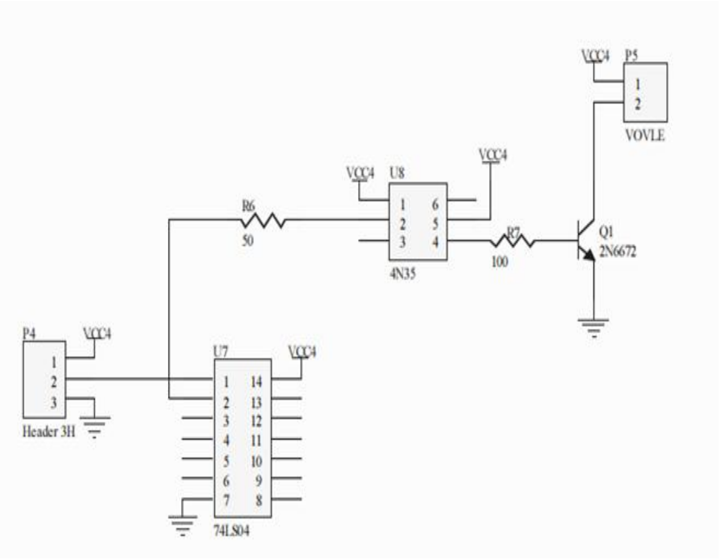
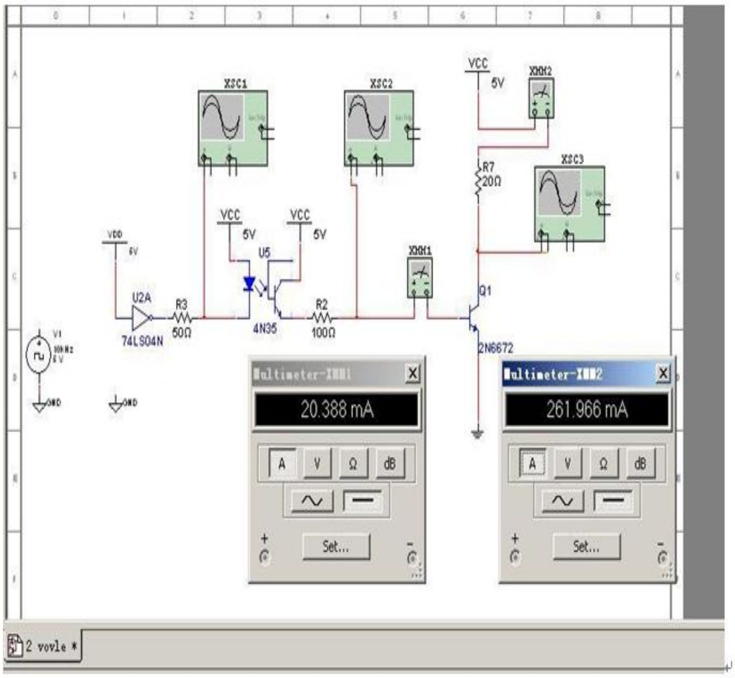


Figure 15: The control circuit of the solenoid valve. (From Altium Designer Schematic, 2001)



Multimeter-XMM1

20.388 mA

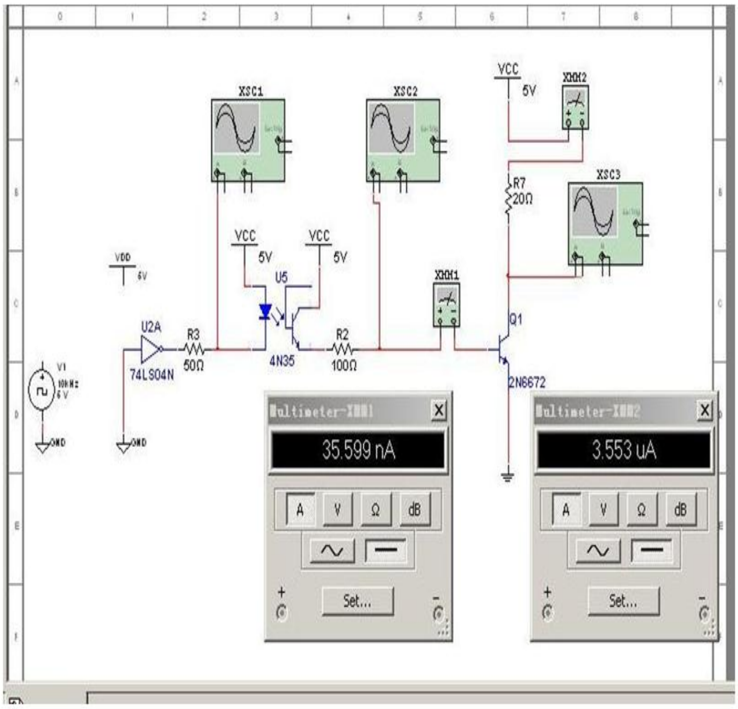
Multimeter-XMM2

261.966 mA

Figure 16: Simulation setup and results for the solenoid valve circuit (From Altium Designer Schematic, 2001)

3.3.4 Simulation of the pump motor control circuit

The pump motor control circuit is especially important as it basically determines whether the ABS is ultimately functional or not: its role is to ensure that the decisions and commands of the controller are effectively transmitted to the pump motor in order to be carried out. Consequently, the main aim of this simulation was to ensure that the decisions of the ABS controller are transmitted in a format compatible with that required by the pump motor. An initial run of the simulation showed that the signal needs to be amplified in order to fit into the range most suitable for the pump motor used. Consequently, an amplifier was used and the final setup and results of the simulation are shown in Figure 16 below.



Multimeter-XMM1
35.599 nA

Multimeter-XMM2
3.553 uA

Figure 17: Simulation setup and results for the pump motor circuit. (From Altium Designer Schematic, 2001)

3.4 Design Evaluation

After the successful validation of the design, the next step was to implement it as a lab prototype and evaluate its performance through some comprehensive tests. The implementation itself consisted in a soldering of all the components required on a PCB board, according to the previously validated design. However, for testing purpose, there was a need also for an experimental setup using a metal gearwheel. The following two subsections describe the PCB board implementation as well as the experimental setup and materials used. The tests and results are then presented and discussed in the remaining subsections of this section.

3.4.1 PCB Board Implementation

A PCB board was used to bring together all the parts of the proposed GMR ABS design. The overall result is shown in Appendix X. The system basically is made of four distinct parts: signal acquisition, signal processing, solenoid valve control and pump motor control. The following paragraphs describe each of these in detail.

The following is a block diagram of the overall system:

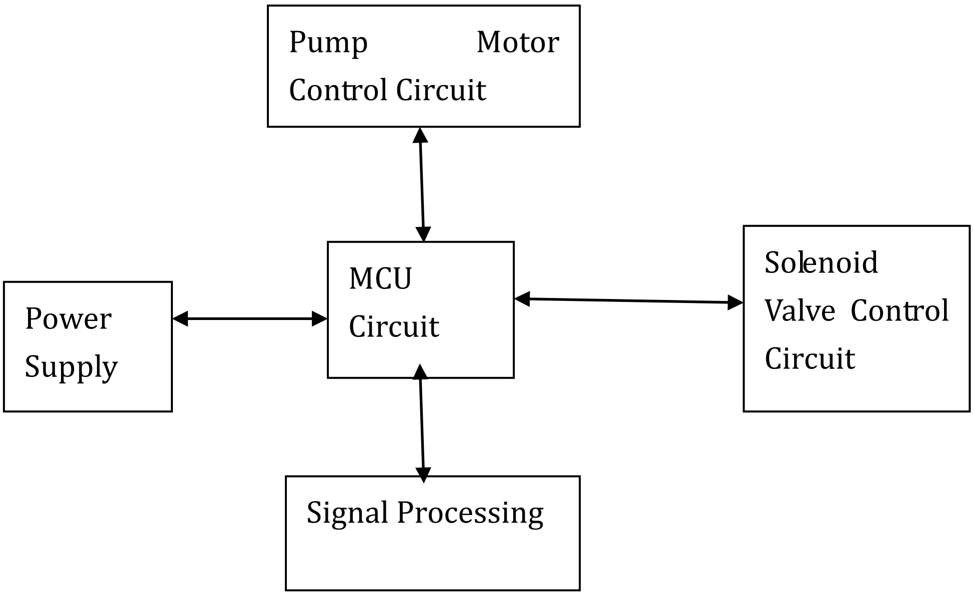


Figure 18: Block Diagram of Overall Circuit

As its name suggests, the role of the signal acquisition part of the design is to reliably collect information from the wheel, regarding its movement. This part includes the GMR sensor array as the actual signal generator, as well as the components that filter and transform the original signal for effective further processing, up to the wireless transmitter. A photo of this part of the prototype is shown in Figure 18.

The second part of the prototype is the main signal processing part. This part receives as input the final signal transmitted by the previous part and it uses it to effectively decide on what action (if any) should be taken. Consequently, the components that make this part are the following: the wireless receiver, the 80C196KC MCU, programming counters and data storage memory. A photo of the main signal processing part is shown in Figure 19.

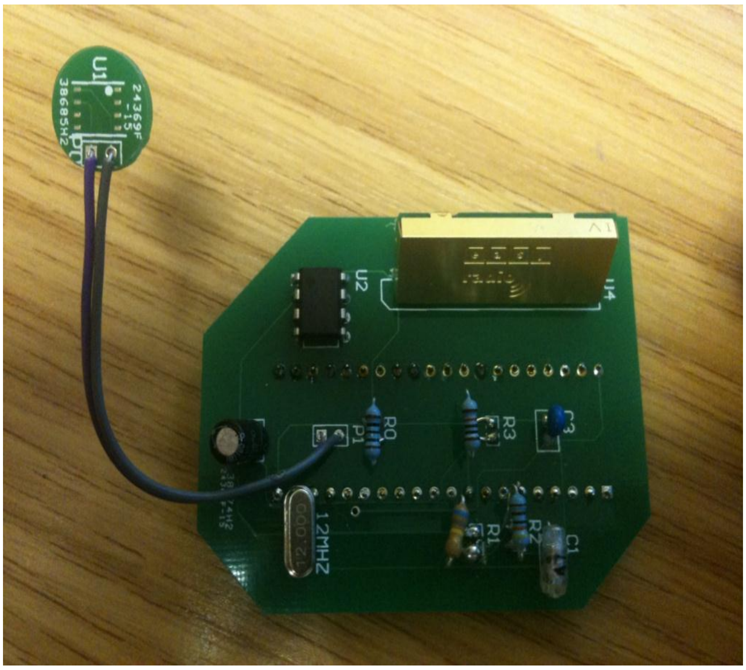


Figure 19: The signal acquisition part of the GMR ABS prototype

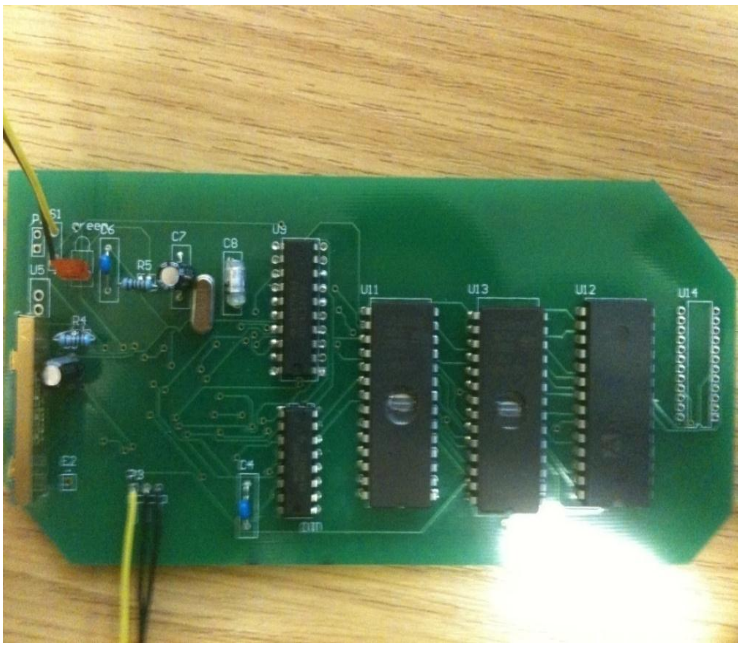


Figure 20: The main signal processing part of the GMR ABS

The decisions made by the main signal processing part of the prototype are then transmitted as commands to the solenoid valve control part. This part includes the phototransistor, hex inverter and channel to the hydraulic valve. This part of the prototype is shown in Figure 20.

The last part of the prototype is the pump motor control part, including the phototransistor, hex inverter and link to the solenoid drive, as shown in Figure 21.

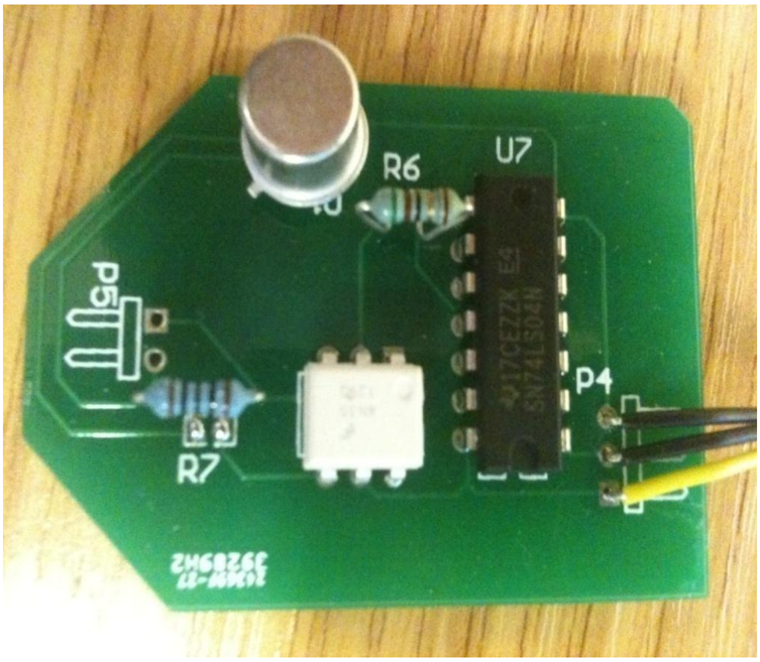


Figure 21: The solenoid valve control part of the GMR ABS prototype

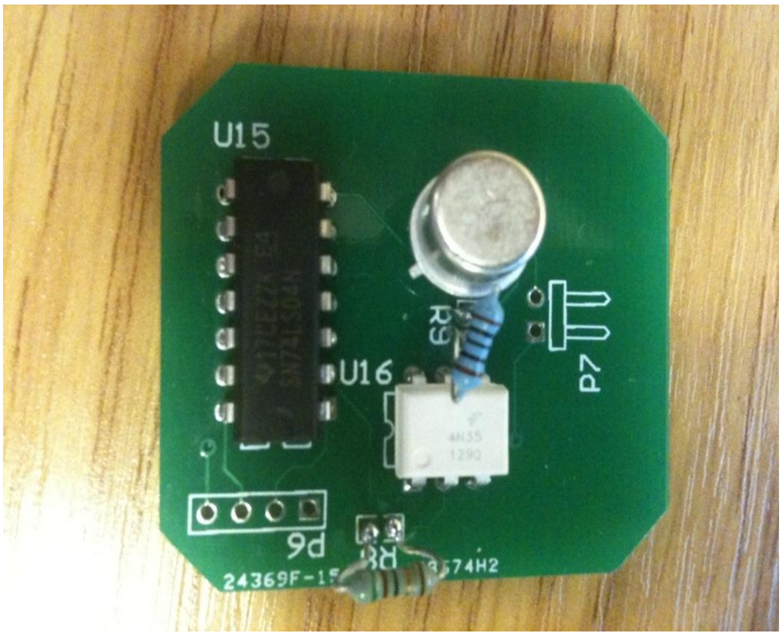


Figure 22: The pump motor control part of the GMR ABS prototype

3.4.2 Experimental Setup

The aim of the experimental setup was to effectively test the functioning of the proposed GMR ABS, through a set of tests run in the lab using the prototype presented in section 3.4.1. Since the actual transmission and transformation of the signal through the various parts of the proposed ABS design was already validated through the simulation, the actual testing of the prototype focused instead on the functioning of the GMR sensor array. This focus is also consistent with the main aim of this dissertation of exploring the potential use and benefits of GMR sensors for ABS, instead of the most usual Hall-effect sensors.

To be able to evaluate the functioning of the sensor itself however, a laboratory setup had to be designed so that the signal is directly collected by the sensor array. Since a full setup involving a motor and wheel was not available, a decision was made to use a more minimalistic, but still adequate setup instead: a metal gearwheel that could rotate on an axis at various speeds and permitting the attachment of the sensor so that different values for the air gap can be experimented with.

The characteristics of the gearwheel can greatly influence the test results and therefore the wheel used for testing was chosen carefully to fit the characteristics of the GMR sensor and to allow at the same time the desired variations of speed and air gap. In particular, the following characteristics were taken into consideration: circular pitch, circular thickness, face width, chordal pitch, and addendum. The shape and strength of the gearwheel are less important for this evaluation, given that the tests focus solely on the behaviour of the sensor at various speeds and air gaps. Nevertheless, a trapezoidal steel gearwheel was chosen, as it is quite common. Figure 22 shows the actual gearwheel that was used for testing.

Figure 23: The gearwheel used for testing the proposed GMR ABS

The gearwheel used for testing has 100 gears around the wheel, an internal diameter of 80.5 mm and an external diameter of 120mm, resulting in a circular pitch of approximately 3.8mm. Consequently, the circular thickness, computed as half of the circular pitch, is 1.9mm. These characteristics are especially important for the choice of motor and they were chosen to fit a motor with a diameter of 80mm. Moreover, the number of gears around the wheel is important to ensure that the frequency generated is within the sensor's measurement range. The value chosen was arrived at by considering the following characteristics and formula for computing the speed:

ABS control speed: 5km/h – 300km/h

Sensor detection range: 1Hz – 10kHz

Speed: $V = 2\pi rf/z$, where r is the radius of the wheel, z is the number of gears and f is the frequency of the sensor's output signal.

The face width of the gears determines the type of expected output from the GMR sensor. For good performance and convenience of measurement of test results, the sensor width should be approximately 4 times larger than the face width, so that a full sine wave should be obtained on the oscilloscope's screen. Consequently, the wheel was chosen so that its face width is approximately 1.8mm. It is important to note that a different wheel with a different face width could have been chosen for testing without significantly affecting the results in terms of actual performance of the sensor in detecting the wheel's movement. However, this setup was preferred simply to have a clear and complete sine wave detected, making the evaluation of the test's results easier.

The addendum and dedendum of the gearwheel were

0.8mm and 1mm respectively. Their values are not particularly important for the type of testing performed, but are given here in order to ensure that a repeatability of the tests can be easily carried out.

Two tests were planned and run:

Test1: basic sensor testing at various speeds. The aim of this test was simply to ensure that the sensor's output is correct for various speeds.

Test2: variation of sensor output depending on air gap at slow speed. The aim of this test was to measure how the output signal of the sensor is affected by the variation in air gap at a relatively slow speed.

For both tests, the sensor was directly attached to the gearwheel that was mounted on an axis. (See figure 23 below). The sensor was fixed to a clamp against the side of the wheel; the rotation of the wheel was then measured through the test circuitry and results obtained (See section 3.4.3 for the test results). The circuitry was powered using a fixed power supply.

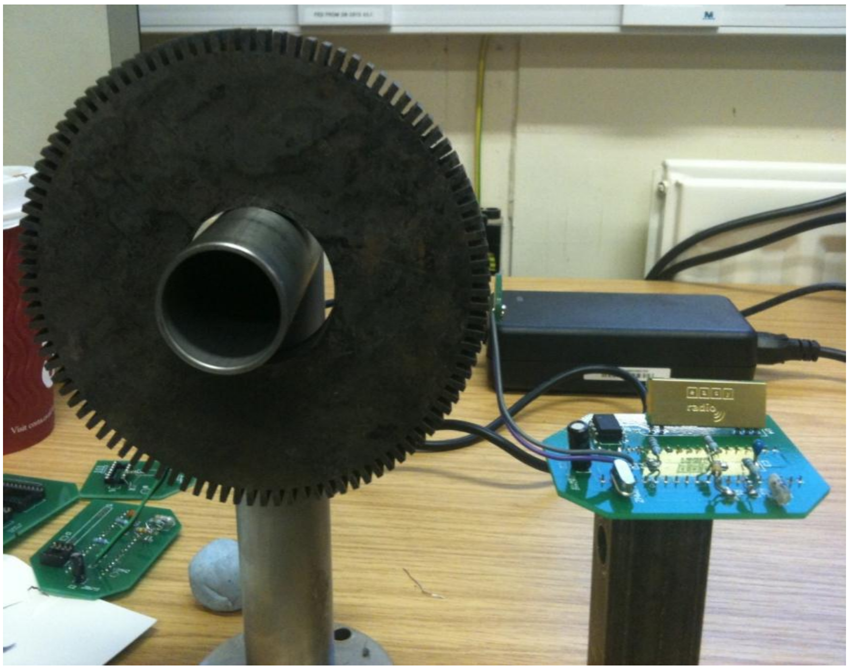


Figure 24: Experimental setup showing the gear wheel and the attachment of the sensor that is connected further to the circuit for initial processing and wireless transmission

3.4.3 Test Results

For Test1, the wheel was first rotated corresponding to a speed of approximately 10mph and the sensor attached so that the air gap was 3mm. The measured frequency and amplitude were 95Hz and approximately 0.5V, respectively. In a second step, the wheel was rotated corresponding to a speed of approximately 60mph, maintaining the sensor attached so that the air gap was 3mm. The measured frequency was 800Hz and the signal amplitude was approximately 5.3V. In both cases, the output signal was consistent and maintained a good sine wave form, as it can be seen in Figure 23, Figure 24, Figure 25 and Figure 26 respectively. The results of both measurements for this test are summarised in Table 3 below.

Speed	Air Gap	Frequency	Amplitude
10mph	3 mm	95Hz	0.5V
60mph	3 mm	800Hz	5.3V

Table 3: Results of Test1, measuring the sensor signal output at various speeds and constant air gap.

For Test2, the wheel was rotated corresponding to a speed of approximately

60mph and the sensor attached so that the air gap variated

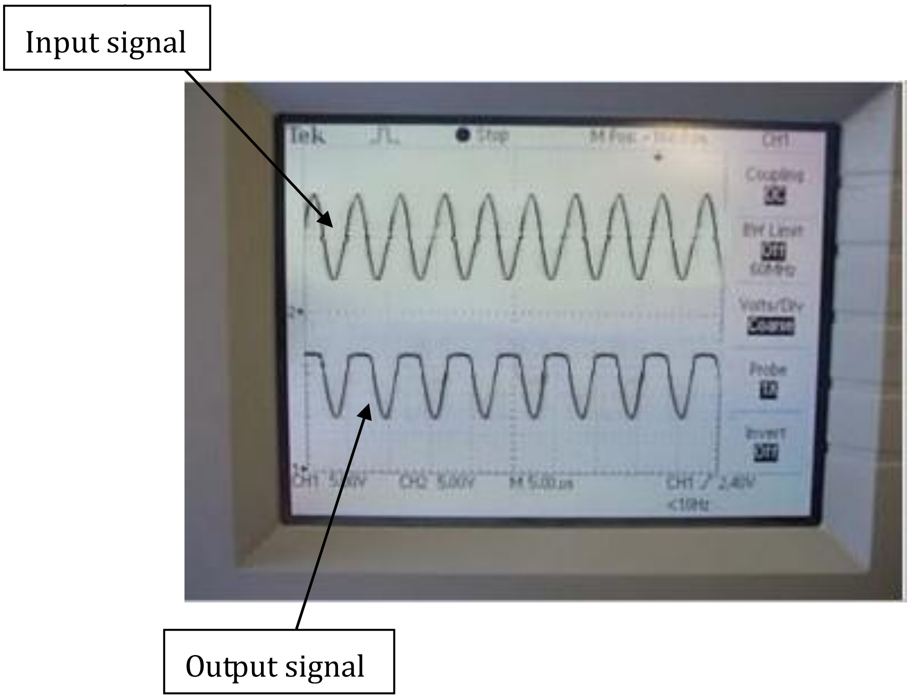


Figure 24: Oscilloscope reading for Test1, at a speed of approximately

10mph and an air gap of 3mm.

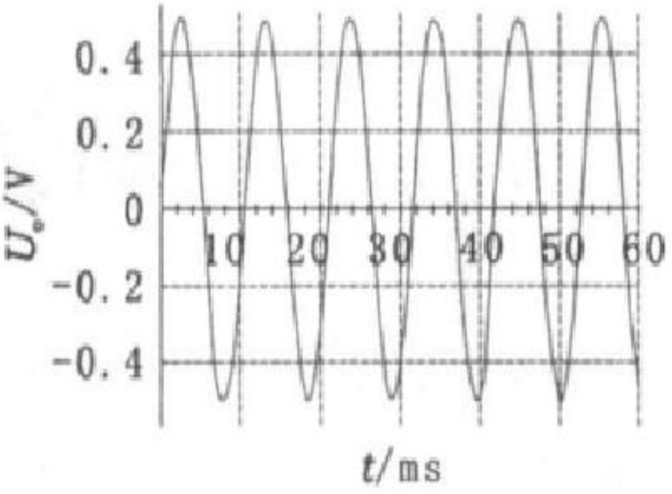


Figure 25: Drawn sine wave corresponding to output signal obtained at 10mph and 3mm air gap (Test1)

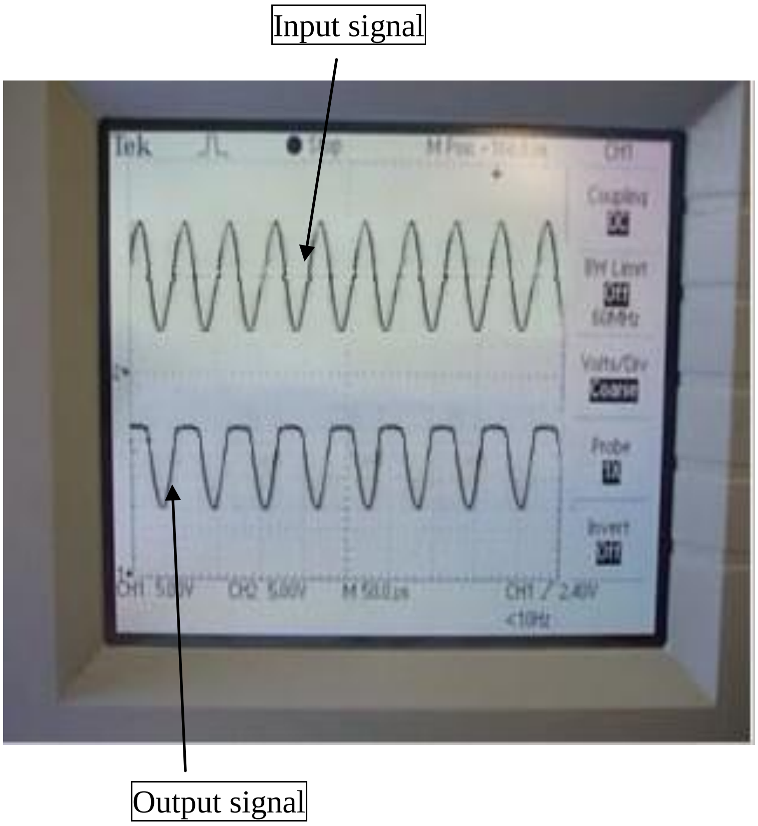


Figure 26: Oscilloscope reading for Test1, at a speed of approximately 60mph and an air gap of 3mm

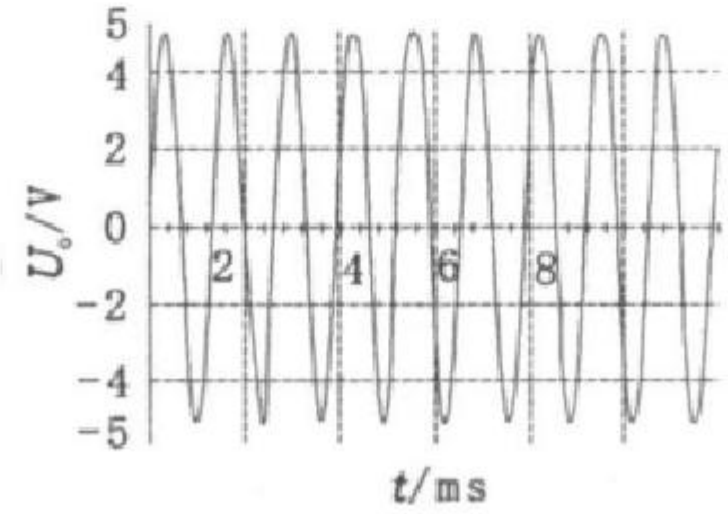
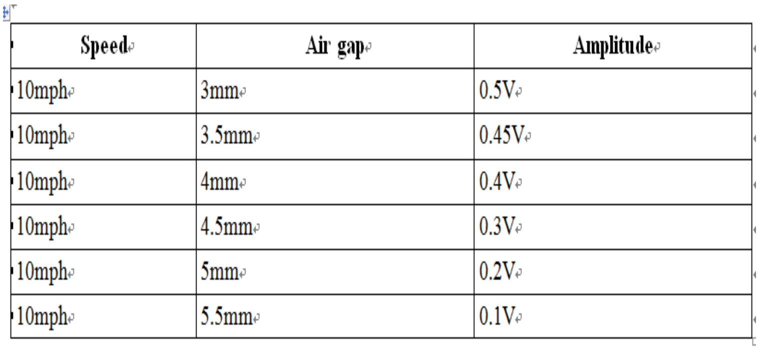


Figure 27: Drawn sine wave corresponding to output signal obtained at 60mph and 3mm air gap (Test1)

For Test2, the focus was on evaluating the sensor's output signal at a relatively slow speed, when the air gap changes. Consequently, the wheel was rotated at a speed corresponding to 10mph and the output signal was measured for an air gap increasing in 0.5mm steps from 3mm to 5.5mm. The results are summarised in Table 4 and shown graphically in Figure 29 below. Two of the signal readings on the oscilloscope are also shown in Figure 27 and Figure 28 respectively.



Speed	Air gap	Amplitude
10mph	3mm	0.5V
10mph	3.5mm	0.45V
10mph	4mm	0.4V
10mph	4.5mm	0.3V
10mph	5mm	0.2V
10mph	5.5mm	0.1V

Table 4: Results of Test2, measuring the sensor signal output at constant speed and different air gaps

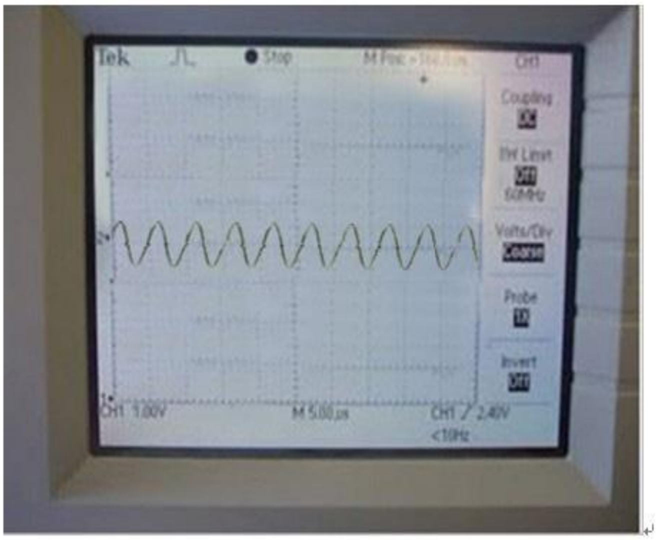


Figure 28: Oscilloscope reading for Test2, at a speed of approximately 10mph and an air gap of 4.5mm

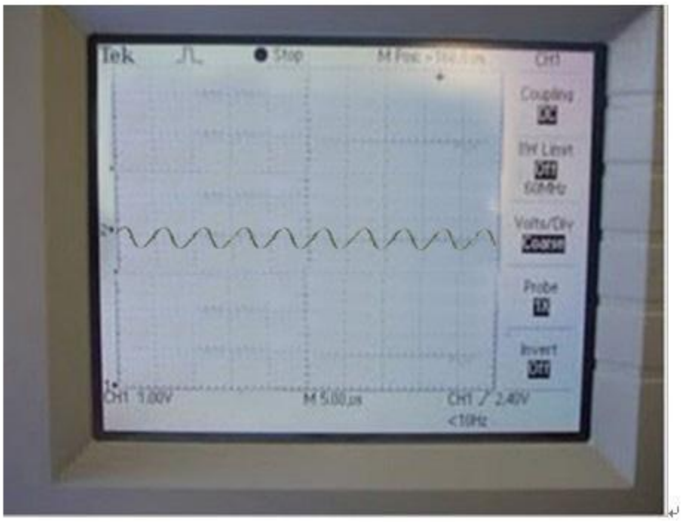


Figure 29: Oscilloscope reading for Test2, at a speed of approximately 10mph and an air gap of 5.5mm

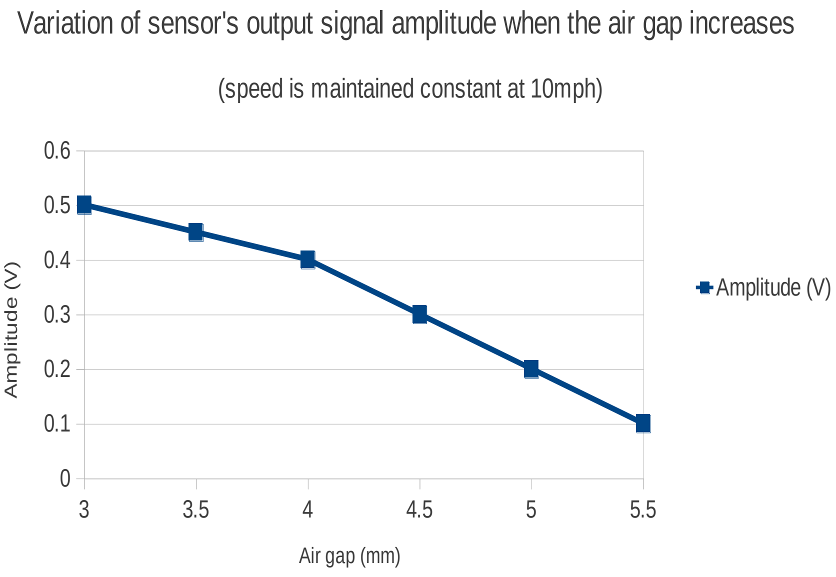


Figure 30: Results of Test2 showing how the sensor's output signal amplitude decreases when the air gap is increased, although the speed is maintained constant

3.4.4 Discussion of Results

The results of the two tests performed for the evaluation of the proposed GMR ABS show that the sensor performs well both at relatively low and at medium speeds. In addition, the investigation of the sensor's behaviour when the air gap increases offers important information about the proposed system's performance in less than ideal conditions. The following paragraphs discuss in more detail the results of each test.

As expected, the first test shows that, when the air gap is maintained fairly low and constant at 3mm, the output signal of the sensor is very clear and with an amplitude that increases when the speed is increased and decreases when the speed is decreased. Moreover, the quality of the output signal from the sensor is very good, as there are no fluctuations of the signal and no apparent noise, as it can be seen from the results presented in section 3.4.3 above. However, it is worth mentioning that these results were obtained in laboratory conditions and therefore, a use of the proposed GMR ABS in real-life conditions might reveal additional interference that can cause the signal to jitter slightly. Nevertheless, the clarity and persistence of the signal in laboratory conditions is a promising result.

The second test investigated the behaviour of the sensor when the air gap is increased. The results essentially show that the sensor offers good and reliable signal output for an air gap in the range of 3 to 5.5mm. Obviously, as expected, the amplitude of the output signal decreases as the air gap is increased, but even at 5.5mm, the signal at 0.1V amplitude is still fairly clear and readable, as it can be seen from the oscilloscope readings shown in section 3.4.3 above. This result is quite important as it reveals the robustness and reliability of the GMR sensor array in less than ideal conditions, when the air gap might increase unexpectedly.

In all situations revealed during the testing, the GMR sensor behaved appropriately, with no apparent loss of signal or significant alteration that might make it difficult for the ABS part to interpret the signal correctly. Consequently, it can be inferred that the

GMR sensor array is likely to be a feasible option to use in ABS, with quite good results. Obviously, additional testing in a wider range of conditions is needed in order to explore the full capabilities and potential drawbacks of using a GMR sensor in an ABS, but this evaluation of a prototype in laboratory conditions shows promising results regarding the quality of the signal and its stability in situations when the air gap increases.

Chapter 4 Comparison of GMR ABS with existing Hall ABS

Given the widespread use of Hall-effect sensors in current ABS designs, this chapter aims to provide a short comparison of the proposed GMR ABS design with the known performances of Hall-effect ABS designs. In particular, the comparison focuses on how each type of sensor performs when the air gap increases.

According to existing literature, the GMR sensor should supposedly offer higher sensitivity compared to Hall-effect sensors. In practice, this should be noticeable through a better quality of the output signal even when the air gap increases. According to the Hall sensor data book, the usual air gap range for which a Hall-effect sensor still offers clear output signal is 0.4mm to 2.5mm (Honeywell, n.d.). By comparison, a GMR sensor supposedly has a range of 1.1mm to 6mm air gap (Honeywell, n.d.).

As it can be seen from the evaluation presented and discussed in the previous chapter, the output signal from a GMR sensor is in fact very strong and clear for air gaps between 3mm and 5.5mm, although at 5.5mm the amplitude of the signal becomes very small. This effectively means that the GMR sensor is indeed capable of better detecting the wheel movement even at air gaps larger than the 2.5mm accepted by a Hall-effect sensor. In addition, when the air gap is around 3mm, the sine wave of the GMR sensor's output signal is very clear and easy to detect and interpret. Consequently, it can be inferred that the GMR sensor can indeed be successfully used for an ABS to increase its performance when the air gap is larger than that for which a Hall sensor can still produce good output signal.

An additional benefit of the GMR sensor that can be inferred from its observed performance during the evaluation is the lower rate of jitter compared to a Hall-effect sensor. Although the jitter was not measured during the evaluation performed for this dissertation, it is known that the higher the sensitivity of a sensor, the lower its jitter. Consequently, given the observed higher sensitivity of the GMR sensor compared to the Hall-effect sensor, it can be reasonably inferred that the GMR sensor is likely to be less affected by jitter as well in situations when the Hall-effect sensor's output might be badly affected by it. This inferred statement is also supported to some extent by the observation that there was little noticeable jitter during any of the situations investigated for the evaluation of the GMR ABS prototype.

Chapter 5 Limitations

The results of this dissertation have to be considered taking into account a series of limitations due mainly to the experimental setup for validation and evaluation. This chapter aims to present and describe the main limitations as well as their potential impact on the applicability of the findings.

The proposed GMR ABS design is meant to explore the use of any GMR sensor for potential improvement of ABS that is used in the automotive industry. However, for practical reasons, the simulation as well as the implementation of the prototype is made with a set of components. Consequently, the findings regarding the sensitivity of the GMR sensor and in particular its good performance in case of increased air gaps have to be interpreted as representative foremost of the components used for to implement the prototype. Generalising these findings to all GMR sensors might not be entirely reliable, as there might be configurations that are more sensitive to interferences for instance or that might be less adequate for certain values of the air gap.

Another important characteristic of the prototype evaluation performed for this dissertation is the fact that a specific configuration of the GMR sensors was used. Therefore, the results obtained are to be considered an indication of the performance of this configuration, rather than a more general indication of GMR sensors as a technology. However, this is not a limitation in itself of the study, given that the purpose was exactly to explore possibilities of using GMR sensors for ABS design improvement, rather than exploring the GMR technology as a whole.

Another limitation of this study is given by the laboratory conditions of the prototype evaluation that was performed. Due to limited resources available, a minimal prototype was built, rather than a fully-working prototype complete with motor and other components. This however limited to some extent the amount and type of testing that could be performed. For instance, there were limited possibilities to adjust and control the speed of the wheel and, consequently, tests were performed for only two speeds rather than on a larger range.

In addition to the above, the setup limited the possibilities of ensuring with high accuracy the constant speed of the wheel. Consequently, the results have to be considered taking into account potential small variations of the speed during the measurement. This was addressed in part by repeating several times each test and measurement so that the results are proven to be repeatable, but nevertheless, a more rigorous control of the speed would have allowed more precise evaluations of other characteristics as well, such as jitter or potential interferences.

Finally, the validation and evaluation of the proposed design focused mainly on the sensor part given that this was the most important novelty proposed. Consequently, the results obtained and discussed in this dissertation are to be considered an indication of the potential improvements that can be obtained from using GMR sensors in the given configuration, rather than an indication of the potential overall performance of the proposed ABS design. As discussed in the following chapter, further investigations should be carried out for a more thorough evaluation of the proposed design as a whole. Nevertheless, it is important to note that the simulation (by contrast to the actual prototype testing) was performed for the design as a whole and therefore it offers reliable proof of the validity of the design in all its parts.

Chapter 6 Conclusions and Future Work

This dissertation explored potential ways to improve the performance of ABS in the automotive industry, focusing especially on the practical use of GMR sensors instead of the widespread Hall-effect sensors and the use of wireless instead of wired transmission of signal data from the sensor to the signal processing and decision part of the ABS.

There are three main contributions made by this dissertation to the body of existing work:

1. An overview of the various types of sensors that are or can be currently used for ABS design, discussing the underlying technology of each as well as their known strengths and weaknesses with respect to potential use in the automotive industry. This overview can help a newcomer to the field to get a clear picture of the main current technologies and the situations in which they can be of use. Moreover, the overview identified GMR sensors as a potential improvement over the most common Hall-effect sensors for use in ABS design. Based on the characteristics of the underlying technology for both types of sensors, the main expected improvement of

replacing Hall-effect sensors with GMR sensors was a better sensitivity that allows accurate information to be collected and transmitted to the ABS system even in adverse situations such as large air gaps that can otherwise compromise the output of Hall-effect sensors.

2. A proposed GMR ABS design that effectively illustrates a potential use of GMR sensors and wireless transmission in a practical ABS. This design provides working solutions for various implementation issues. Such solutions include for instance an efficient working configuration for an array of GMR sensors and the needed circuits to process and transform the output signal so that it can be wirelessly transmitted and further processed and interpreted by the main control unit of the ABS. In addition, the design is fully validated through a simulation that involves all its component parts. A working prototype is then implemented and physically tested in the laboratory, providing measurements and proofs of the functioning of the GMR sensor at various speeds and different air gaps.

3. A comparison of the observed (measured) characteristics of the GMR sensor's performance in the proposed ABS design with the known

characteristics of standard Hall-effect sensors. This can help the industry as well as any other stakeholder who is interested in potential alternatives to Hall-effect sensors, effective ways to improve the performance of an ABS design.

The main finding of this dissertation is that GMR sensors and wireless transmission can indeed be successfully used to improve the sensitivity of ABS. The full design developed, combined with the validation and evaluation results offer proof that this is indeed the case. However, the work presented in this dissertation should be considered as only an initial step towards the full exploration of the potential of GMR sensors for improving the performance of ABS. Considering the exploratory nature of the work, its results are meant primarily as initial proofs of the validity and potential of the approach, rather than definite evidence of the exact improvements to be gained from the use of GMR sensors and wireless transmission in the design of ABS. For such definite evidence to be obtained, several directions should be further explored in future work that can build on the results of this dissertation, as described in more detail in the following paragraphs.

The first direction of future work that stems from this dissertation is the more detailed and thorough evaluation of the behaviour of GMR sensors in implementations of ABS and in real-life situations. The results of the laboratory evaluation showed better sensitivity and clear, jitter-free output signal from the sensor array. However, a more complete prototype should be built and tested in a variety of situations including for instance variations of temperature, extreme road and speed conditions as well as potential interferences from other sources. Moreover, the actual performance of the GMR sensor array should be further assessed on all the expected range of speed and air gaps that could occur in-use situations. This would offer a more comprehensive image of the actual improvements offered by the use of GMR sensors as well as valuable information regarding any potential drawbacks or situations when the GMR sensor array might offer a less clearer or reliable signal than expected.

Another important aspect that would benefit from future work is the testing of the wireless transmission used in the proposed GMR ABS design. The simulation validated the complete design, but it could not take into account for traffic situations and the potential interference that might obstruct or otherwise reduce the efficacy of the wireless transmission. Consequently, future work should focus on testing thoroughly this part of the proposed design as well, in order to ensure that the wireless transmission is equally reliable to a wired one even in extreme traffic situations when the ABS is often most needed to avoid potential accidents. Such testing could also reveal potential issues with the wireless transmission that were not obvious during the validation and evaluation performed as part of this project, given the laboratory conditions and limited resources available. Nevertheless, a thorough evaluation of the wireless transmission is certainly needed before it can be considered as a fully safe alternative to replace cumbersome wired transmission in mass produced ABS designs.

The work done for this dissertation essentially offers one effective way in which GMR sensors can be used to enhance ABS design. However, the sensor array proposed as well as the configuration used are not necessarily the only possible or even most efficient ways of harnessing the benefits of GMR sensors for improved ABS performance. Therefore, another direction for future work would be to explore the performance of other configurations or other potential ways in which GMR sensors could improve the functionality of an ABS. For instance, the higher sensitivity of the GMR sensor compared to the Hall-effect sensor basically offers more precise information to the main control circuit of the ABS and such information could in turn be used to take more precise and more effective decisions in potentially dangerous traffic conditions to improve both the safety and convenience of driving.

Finally, another direction for future work would be the more detailed comparison of GMR and Hall-effect sensors when used for ABS design. The comparison performed for this dissertation was limited by the relatively little information available from the experimental setup. Although useful with respect to comparing the sensitivity of the two types of sensors, a more comprehensive comparison would be needed in order to fully inform a potential decision of using one sensor type or the other in an ABS design. First of all the comparison of sensitivity itself could take for instance into account more variate operation conditions including a wider range of speeds and air gaps as well as interferences that can introduce jitter or otherwise affect the quality and adequacy of the information obtained and transmitted by each type of sensor in a real-life situation of use in traffic. Second, a comprehensive comparison should also include other aspects such as the behaviour of the two types of sensors in extreme conditions and their resilience to unexpected situations as well as their stability of operation in time or over extended periods of intensive use.

Overall, the work presented in this dissertation represents an initial successful exploration of some of the ways in which current ABS design can be improved through the use of GMR sensors and wireless communication. As reflected in the variety of directions available for future work, the results of this dissertation open a large number of paths that can lead to potentially significant improvements of ABS design that can result in both safer and more enjoyable driving, adequate for the increasingly complex traffic situations that are current on modern roads all around the world.

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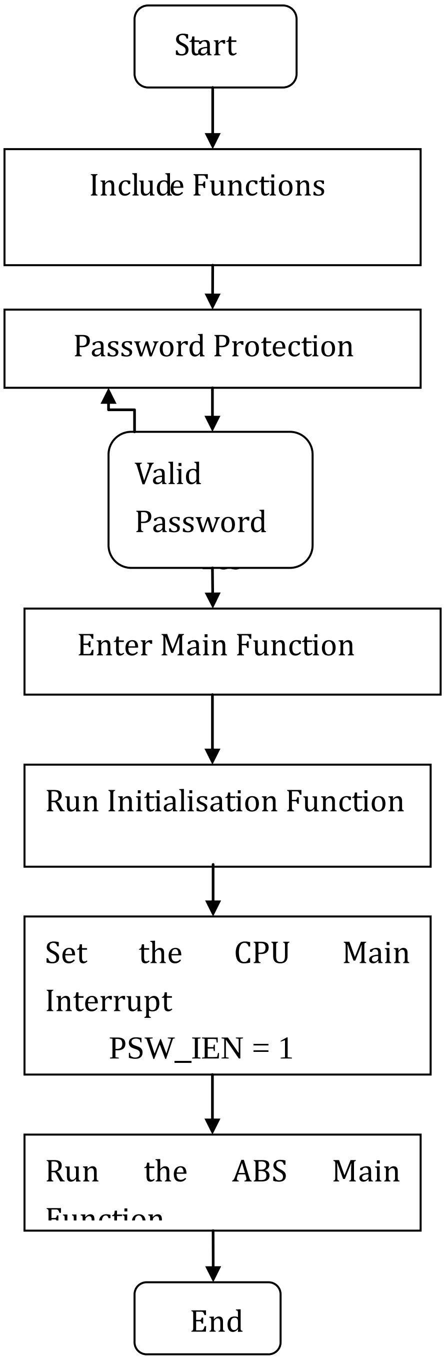
Appendix

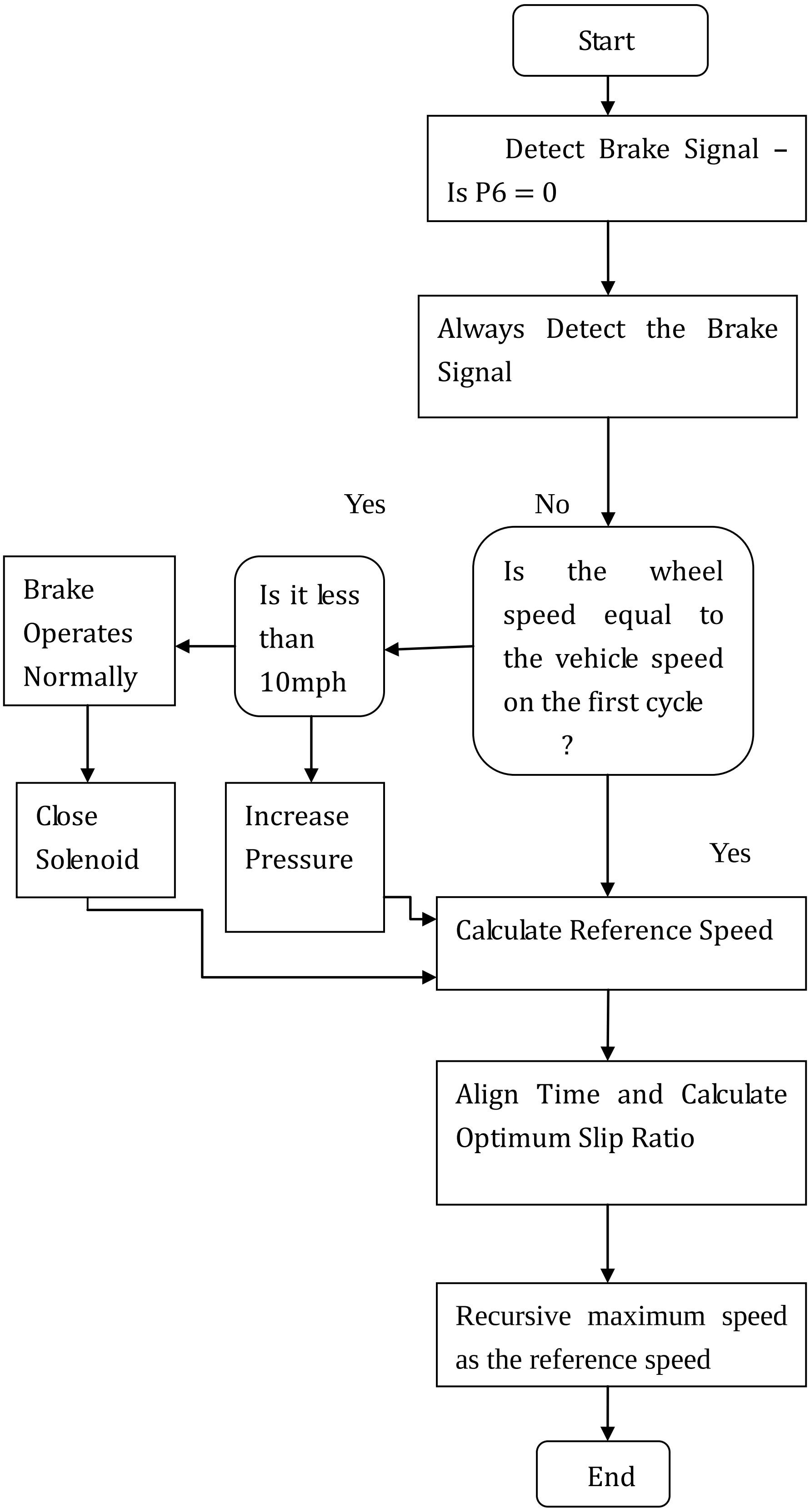
Appendix I ----Flowchart of Source File of 80C196KC

Main function



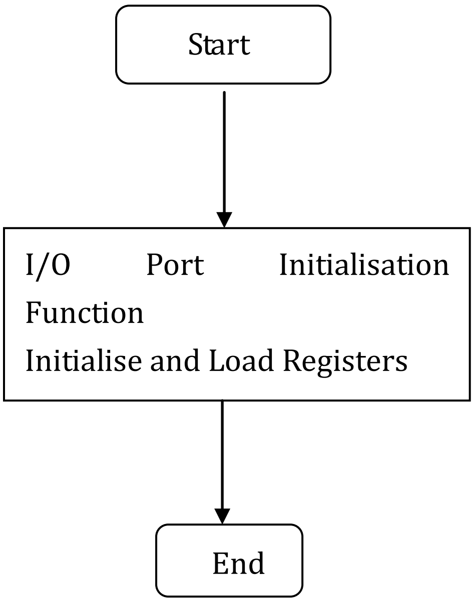
Appendix II ---- Flowchart of Source File of 80C196KC

ABS main function program



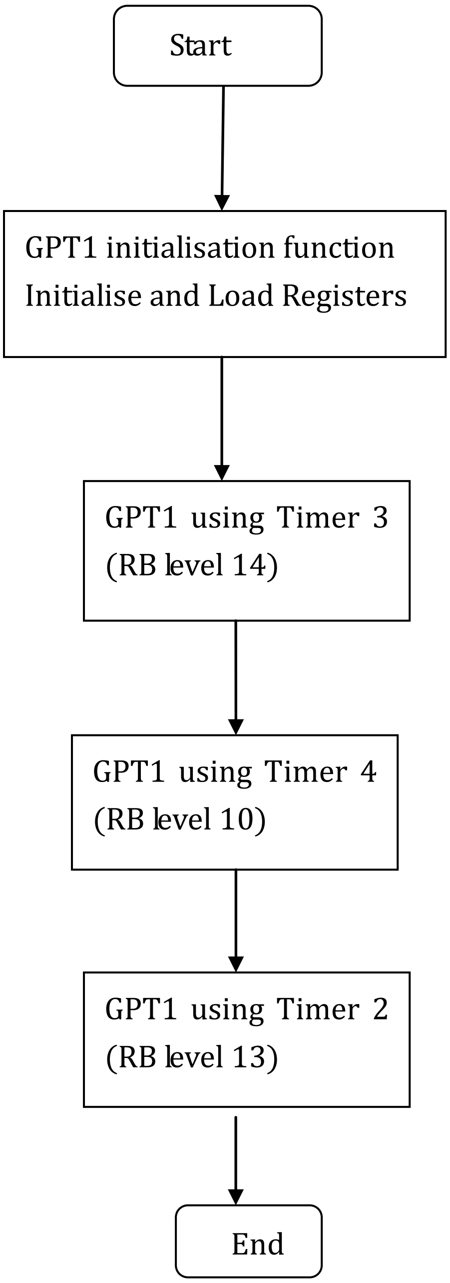
Appendix III ---- Flowchart of Source File of 80C196KC

Input and output port initialisation function



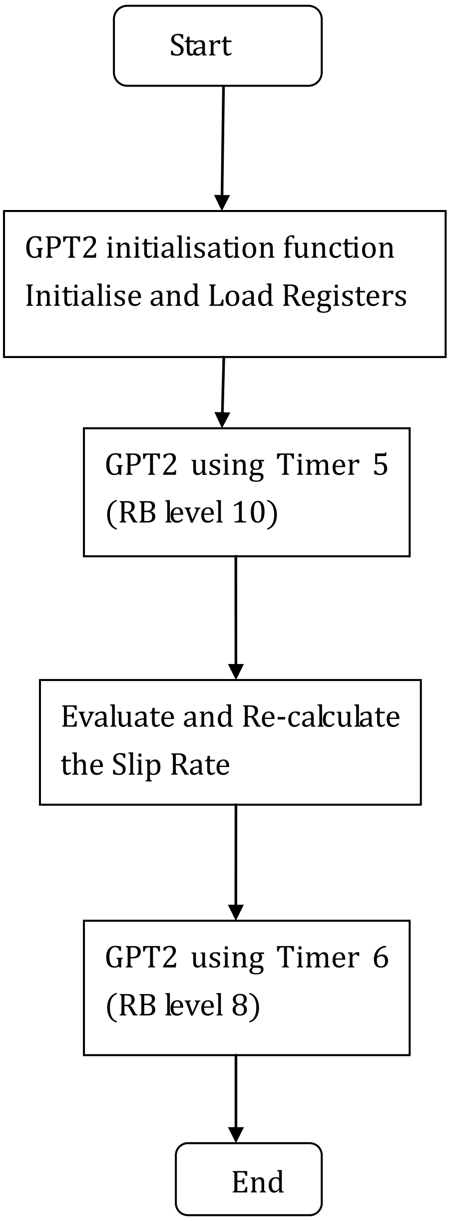
Appendix IV ---- Flowchart of Source File of 80C196KC

GPT1 unit interrupt function



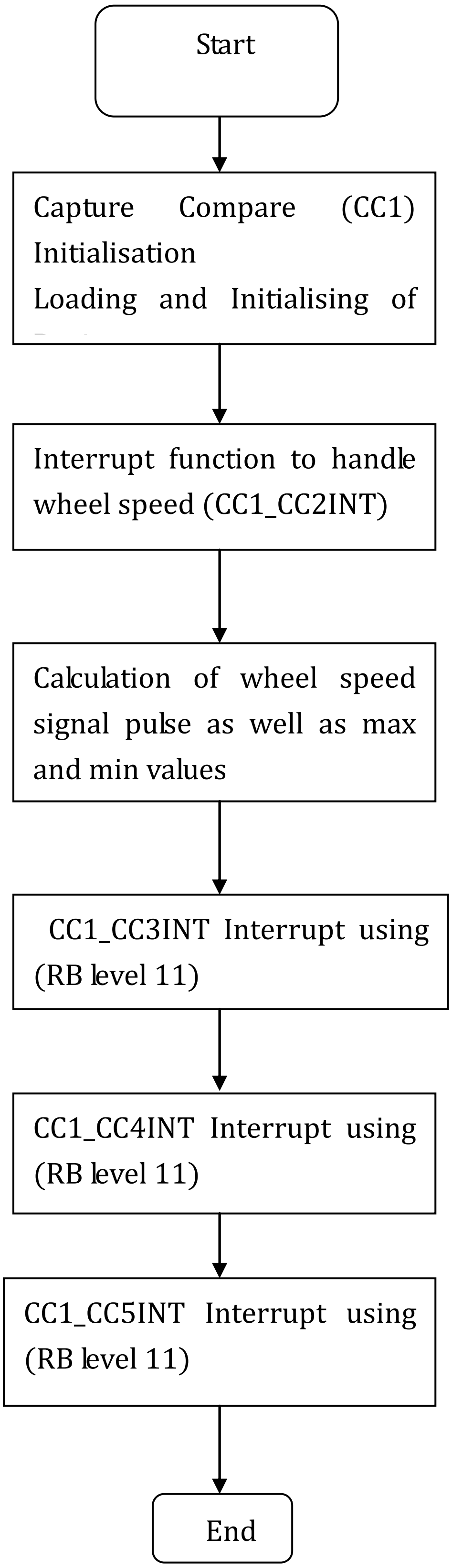
Appendix V ---- Flowchart of Source File of 80C196KC

GPT2 unit interrupt function



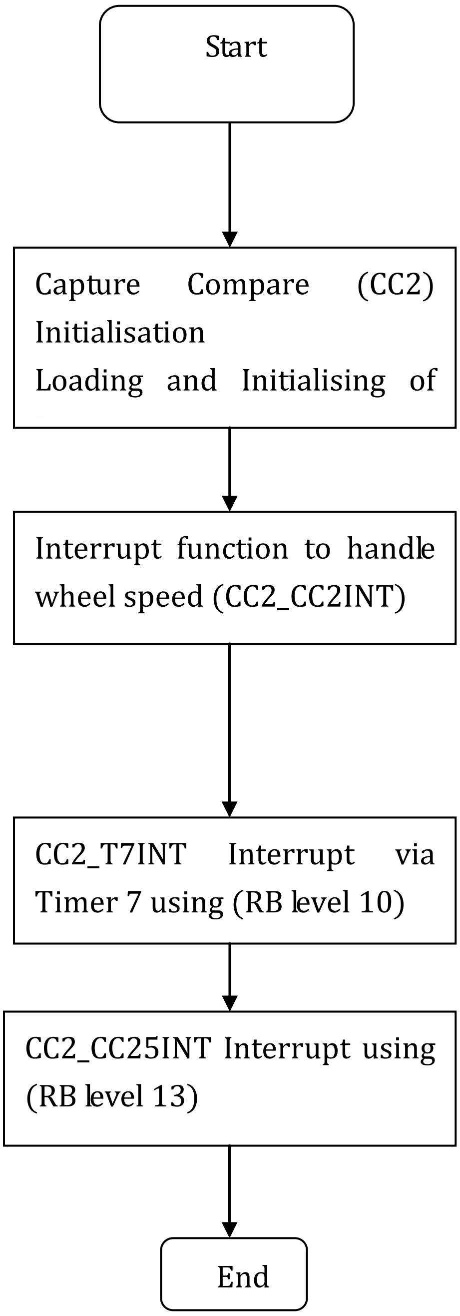
Appendix VI ---- Flowchart of Source File of 80C196KC

CC1 wheel speed interrupt processing function



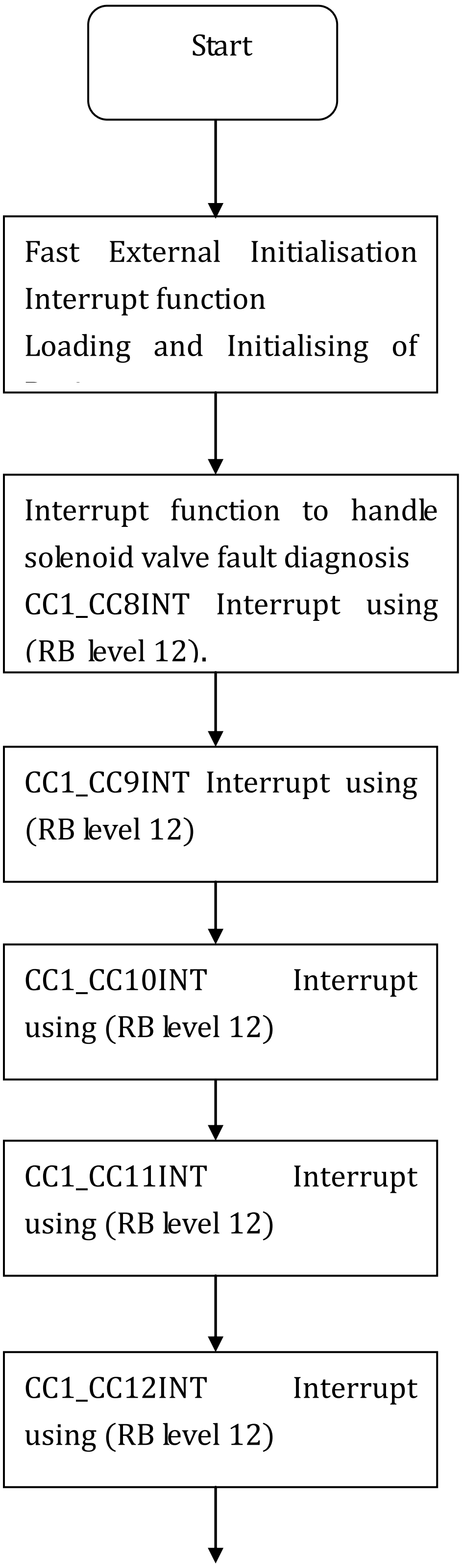
Appendix VII ----Flow chart of Source File of 80C196KC

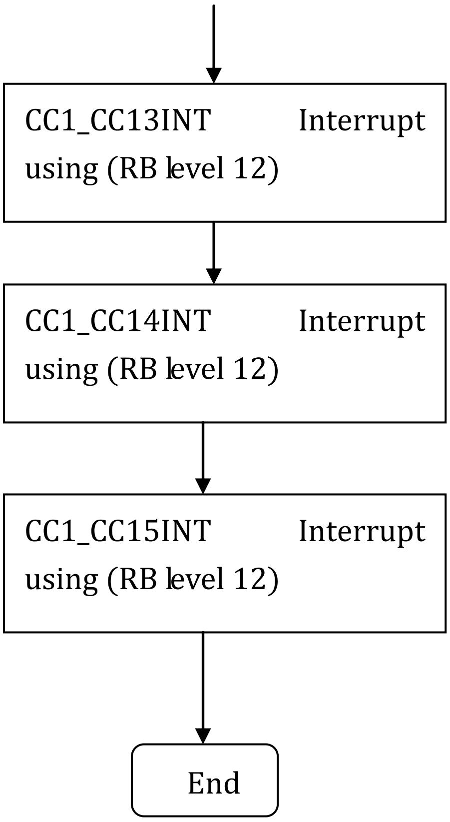
CC2 wheel speed interrupt processing function



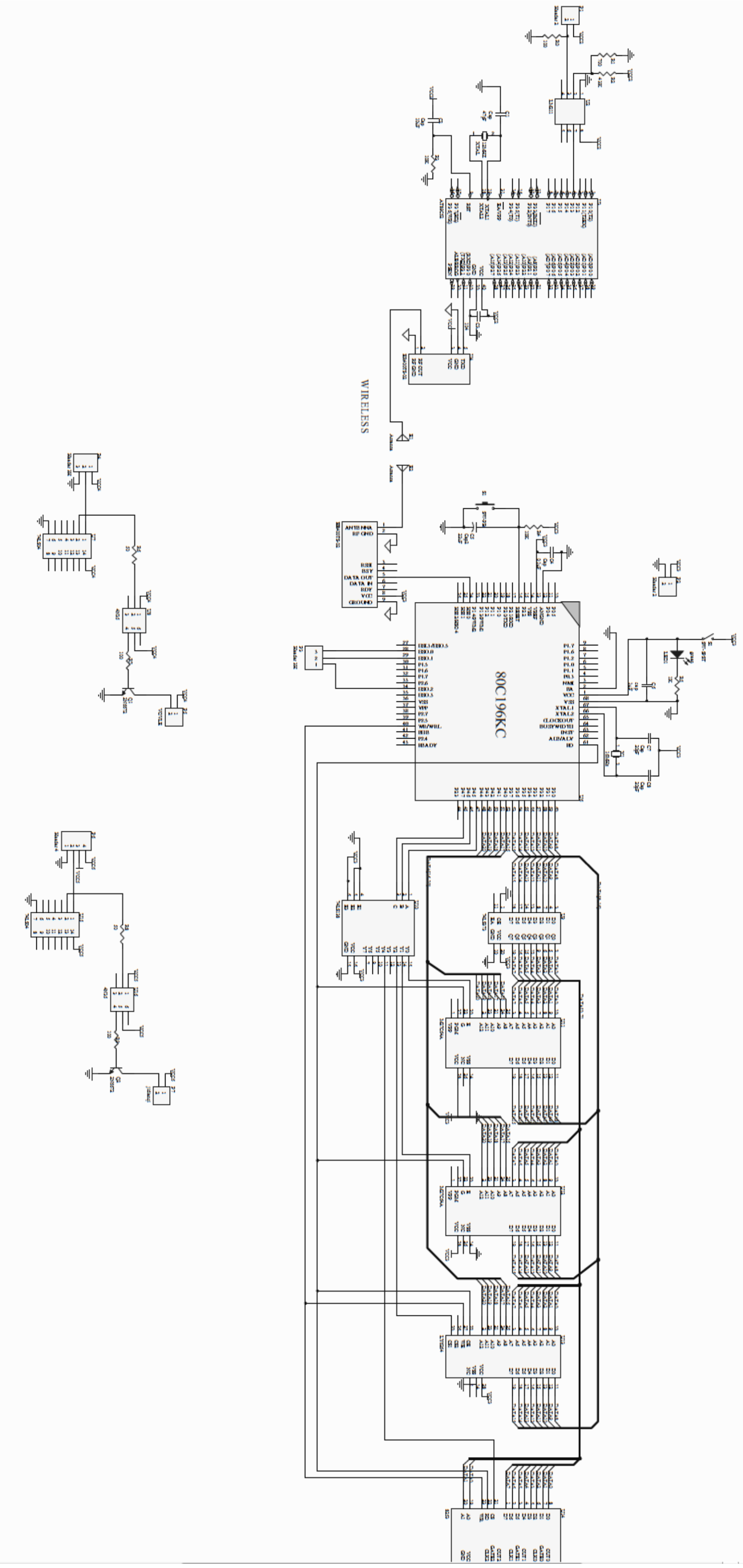
Appendix VIII ---- Flowchart of Source File of 80C196KC

Fast external interrupt initialisation function




CC1_CC13INT Interrupt using (RB level 12)
CC1_CC14INT Interrupt using (RB level 12)
CC1_CC15INT Interrupt using (RB level 12)
End

Appendix IX The full design circuit of the ABS system



Appendix X The Layout Design of the ABS System