Designing an innovative brake system

BAP Thesis | E-Brake | Hitch Connection Unit

by

Samuel-Anton Jansen (4370333)
Maurice Willemsen (4366662)

Client:	E-Trailer
Supervisors:	dr.ir. H. Polinder
	ir. F. Wani
	ir. R. Lenssen
Thesis committee:	dr.ir. H. Polinder
	prof.dr.ir. A.J. van der Veen
	dr.ir. M. Ghaffarian Niasar
Project duration:	April 24, 2017 – July 7, 2017

This thesis is confidential and cannot be made public

TU Delft Delft University of Technology

Abstract

This thesis is written as part of the Electrical Engineering bachelor graduation course at Delft University of Technology. It describes the design of a subsystem of the E-Brake developed by E-Trailer B.V. The E-Brake is an innovative brake system for trailers that uses electronically controlled brakes to brake a trailer. This will minimize the influences a driver experiences from the trailer during braking. The horizontal force the trailer exerts on the car during braking, is the main contributor to this experience. The described subsystem, the hitch connection unit, measures this force.The force measurement is done using a load cell in the hitch connection and an A/D converter. An microcontroller communicates this force via a CAN bus protocol to the rest of the E-Brake system. The other parts of the E-Brake calculate and exert the needed braking force for the trailer. The used communication system and protocol will also be discussed. The final E-Brake system is tested as a whole. From these test results can be stated that the system operates as it should and that the described subsystem in this report works correctly.

Contents

Abstract **iii**

1 Introduction **1**

1.1 Context . . . 1
1.2 Problem Definition . . . 2
1.3 Thesis Synopsis . . . 2
1.4 State of the Art Analysis . . . 2

2 Program of Requirements **5**

2.1 Functional Requirements . . . 5
2.2 System Requirements. . . . 5
2.3 Manufacturing requirements . . . 6

3 Design Process **7**

3.1 System Design . . . 7
3.1.1 System Overview. . . . 7
3.1.2 Design Synopsis . . . 8
3.2 Force Sensor . . . 9
3.2.1 Types of force sensors . . . 9
3.2.2 Capacity . . . 9
3.2.3 Accuracy . . . 10
3.2.4 Sensitivity . . . 11
3.2.5 Power consumption. . . . 11
3.3 A/D Converter . . . 11
3.3.1 Requirements . . . 11
3.3.2 Comparison . . . 13
3.3.3 Anti-Aliasing filter . . . 13
3.3.4 Accuracy . . . 14
3.3.5 Output characteristics. . . . 14
3.3.6 Circuit . . . 14
3.3.7 Power Consumption . . . 14
3.4 Communication Protocol . . . 14
3.4.1 Physical layer . . . 15
3.4.2 Data-Link layer . . . 16
3.4.3 Other layers . . . 17
3.4.4 Application layer . . . 17
3.4.5 Possible Problems . . . 18
3.5 Microcontroller. . . . 19
3.5.1 Requirements . . . 19
3.5.2 Comparison of available microcontrollers . . . 19
3.5.3 Circuit . . . 20
3.5.4 Power Consumption . . . 22
3.6 Voltage Converter . . . 22
3.6.1 Requirements . . . 23
3.6.2 Circuit . . . 23
3.6.3 Output Characteristics . . . 25
3.6.4 Accuracy . . . 25
3.6.5 Power Consumption . . . 26

3.7 Processing . . . 26
3.7.1 Main concept . . . 26

4 Prototype and Validation 29
4.1 Implementation . . . 29
4.1.1 PCB . . . 29
4.2 Results . . . 29
4.2.1 Load cell . . . 29
4.2.2 Whole E-Brake system . . . 30
4.2.3 Brake System . . . 32

5 Discussion 35
5.1 PCB . . . 35
5.2 Force Measurement . . . 35
5.2.1 Newton meter test . . . 35
5.2.2 Whole E-Brake system test . . . 35
5.2.3 Spikes . . . 35
5.2.4 Offset . . . 36
5.2.5 Other observations . . . 36
5.3 Voltage Measurement . . . 36
5.4 Communication . . . 36
5.5 Brake System . . . 37

6 Conclusion 39

A Appendix 41
A.1 Selected RDW requirements . . . 41
A.2 CAN protocol . . . 44
A.3 PCB . . . 46
A.3.1 Layout . . . 46
A.3.2 Pinouts . . . 47
A.4 Results . . . 48
A.4.1 Force Measurement . . . 48
A.4.2 Voltage Measurement . . . 49

Bibliography 51

1 Introduction

1.1 Context

More and more trailers are seen on the road. These could be small caravans or big transport trailers for trucks. Towing a trailer makes driving a car feel different. The driver needs to take turns carefully and driving in reverse is a real challenge. The swinging of the trailer could be a big problem as well and during braking, it feels like if the trailer is pushing the car forward. Because of the previous mentioned aspects, driving a car-trailer combination feels very different in aspect to driving a car without a trailer. In order to minimize the influences of the trailer on the driving experience of the driver, an innovative electronic brake system is developed. The most important aspect of this system is to minimize the influence of the trailer on the driving experience of the driver.

E-Brake

The E-Brake is an electronic brake system for trailers. The system uses electronic controlled brakes on the wheels of the trailer. The **brake controller unit (BCU)** controls the brake force on the wheels using a solenoid. A PWM controlled current drives this solenoid which then will clamp on the wheel. The solenoid will be pulled along with the rotating wheel. Because the solenoid is also mechanical secured to the drum brake, the brake shoes will be pushed outward decelerating the wheel. The amount of deceleration depends on the clamping force of the solenoid. A transistor is powered by a DC-DC converter, which is connected to the car battery and an extra buffer battery inside the trailer. This transistor provides the current for the solenoid to clamp on the wheel. It is switched on and off by the PWM signal generated by a microcontroller. This microcontroller calculates the correct dutycycle based on the force specified by the MPU.

The **main processing unit (MPU)** computes the required brake force via a control model of the whole brake system and the trailer. For this model all kind of parameters are needed. The most important parameters which the MPU needs, are the horizontal force of the trailer acting on the car and the brake signal from the car. When the MPU receives this brake signal, it will calculate which brake force is needed to neutralize the force between the car and the trailer.

In order to neutralize this force, the MPU needs to know what the current force is. This force needs to be measured at the connection between the car and the trailer, at the hitch. To obtain the best results, an separate module needs to be placed at the hitch which needs to be developed especially for measuring the horizontal force. Therefore a third module is developed: the **hitch connection unit (HCU)**. This module needs to not only measure this horizontal force, but also to communicate it to the MPU. Because the HCU is closest to the car, it will also need to monitor when the car is braking or not.

In order to let the different modules communicate with each other, a protocol for communication needs to be set up.

The E-Brake system thus consists of three subsystems, as can also be seen in Figure 1.1. This thesis will go further in detail about the design of the HCU and the used communication protocol.

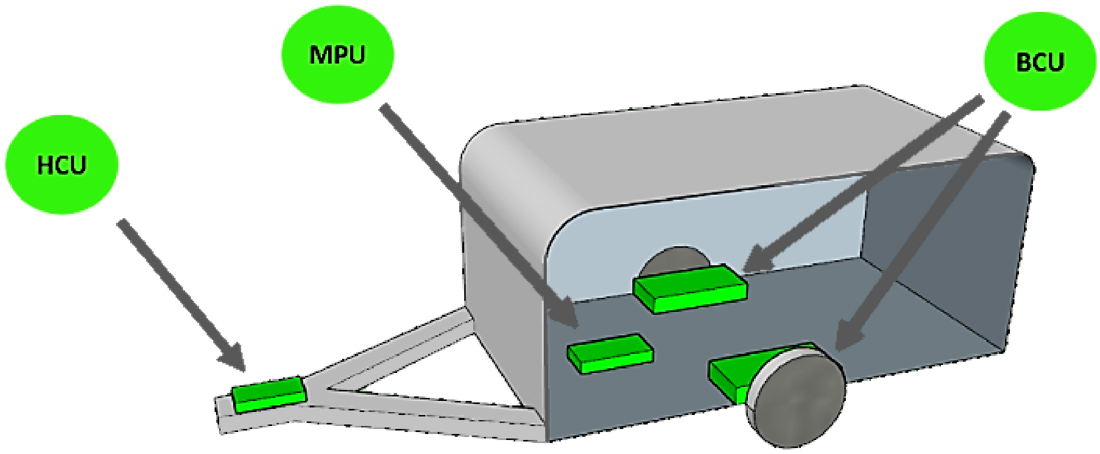

Figure 1.1: E-Brake overview

1.2 Problem Definition

Like stated in the previous section, the problem is that the driver of a car with a trailer experiences the influences of the trailer while driving. In order to remove these influences during braking as much as possible, the force acting between car and trailer should be minimized as much as possible. The main problem can be defined as: “Design an electronic control system for an innovative brake system for trailers”. The contribution of this thesis to this problem is measuring and communicating the force acting between the car and the trailer. Therefore the problem definition for this thesis is: “Design a system that measures the force acting between a car and a trailer, and that communicates this force to the main processing unit of the brake system”.

1.3 Thesis Synopsis

In the next section of this chapter a state of the art analysis is given. This will describe the current market and products for electronic brake systems for trailers. In chapter 2, the requirements for the brake system that are important for the HCU and the communication protocol are listed. In chapter 3, the whole design process of the HCU will be elaborated. Thereafter, in chapter 4, the build prototype is described and tested. These test results are discussed in chapter 5. At last, a conclusion and some recommendations about the whole HCU are given in chapter 6.

1.4 State of the Art Analysis

Currently, a few brake systems exist for trailers. The most used brake system uses a overrun brake to activate the brakes. This works very simple: when the car brakes, and thus the trailer pushes on to the car, a spring inside the hitch connection gets activated. This spring tightens the cables to the brakes, decelerating the trailer. This system brakes long and powerful enough up till the force between the car and the trailer neutralizes. Disadvantage of this system is that when the car drives in reverse, the spring will also tighten and the brakes of the trailer are activated. Another problem is that during driving downhill, the trailer will push against the car. This causes a constant activation of the brake system of the trailer. When driving in the mountains for example, the brakes can overheat and replacement will be needed. Systems exist which can omit this brake system temporally, but these are illegal.
The E-Brake is a legal system which meets the RDW requirements. This system automatically prevents

actual braking when the car is reversing. Also, the system can detect when the trailer is driving downhill. The system then will act accordingly to prevent the brakes from overheating. Overheating is also prevented by taking the brake temperatures into consideration when braking.

Next to mechanical brakes, electronic brake controllers for trailer also exists. These controllers can be activated in two ways. The controller controls the brake force of the trailer depending on the deceleration of the car [1]. This brake force is proportional to the deceleration. Other systems use the brake signal from the brake lights of the trailer to detect braking or they use a sensor on the brake pedal. Both systems may use different kind of brakes. The brakes can be activated by an electric motor pulling the cables for the brakes, or by electric controlled hydraulics or pneumatics. Another type of brake, which is quite rare in Europe in comparison with the United States of America, is the electric brake. This is the type of brake that is also used in the E-Brake and is described previously in section 1.1. The advantage of these electric brakes is that they can be controlled individually. This is useful when implementing an anti-swaying system.

These electronic brake systems may be easy to implement, but they are not ‘smart’. They are designed to assist the driver during braking, but not to optimally neutralize the pushing force of the trailer on the car. They do not take the horizontal force between the car and trailer into account. The E-Brake will not only activate the brakes, but also control these brakes in such way that both wheels decelerate in the same amount. Also, the E-Brake can be developed to prevent swaying of the trailer, which the current brake systems certainly cannot do. The E-Brake thus has fare more control than the current available brake systems and it is more efficient.

2

Program of Requirements

This chapter describes the requirements that are important for the HCU. Most important are the requirements specified by the RDW, the Dutch institution that determines the rules for cars and other vehicles on the road. For trailers a large amount of requirements are also specified. Only the important requirements towards the E-Brake are selected and merged into the requirements. The selected requirements can be found in appendix A.1. For the requirements in this chapter that correspond to RDW requirements, the corresponding number in the appendix is notated between the parentheses.
The program of requirements for the hitch connection module is listed below.

2.1 Functional Requirements

1. The system must measure the force which the trailer exerts on the car.
2. The system must be able to detect if the car is braking.
3. The system must be able to detect if the car is driving in reverse.
4. The system must be powered by the battery of the car.
5. The system must measure its supply voltage.
6. The system must communicate with the other parts of the E-Brake.

2.2 System Requirements

Overall

7. The system must cope with vibrations (1).
8. The brake must only react on valid brake signals (8-10).
9. The system may not illuminate the brake lights (12).
10. Errors in the system must be detected and made noticeable (7)(11).
11. The system must be able to handle the horizontal force at a deceleration of 9.8m/s^2 without breaking or plastically deforming. This is the maximum deceleration due to braking of a car with ABS. [2]
12. The delay of the total system must be less than 600ms (14).
13. The maximum weight of the trailer on which the system is implemented, is 1800kg.
14. The voltage of the car battery may not drop below 9.6V at a maximum current consumption of 15A (4)(18).

Measurements

15. The system must be able to measure changes in the horizontal force between the car and the trailer at a deceleration of not more than $0.4\mathrm{m/s}^2$ (20).
16. The system must be able to measure this horizontal force up to a deceleration of at least $5.9\mathrm{m/s}^2$ (21).
17. The measurement result may not be influenced by electric and/or magnetic fields (2).
18. The supply voltage must be indicated at 1 decimal precision with an accuracy of 100mV.

Broadcasting

19. The system must immediately broadcast the reverse and brake signal of the car when these are detected.
20. The system must broadcast the brake and reverse signal at least once every 100ms.
21. The system must broadcast the measured force and voltage at least once every 100ms.

Protocol

22. The most important data transfers must have an higher priority than less important transfers.
23. The brake force signals for the brakes of the trailer must have the highest priority.
24. Any module may not monopolize the communication bus.

2.3 Manufacturing requirements

25. The system must be designed in such format that the hardware of it (exluding sensors) will fit in the same casing as the E-Connect of E-Trailer [1].
26. The system must be designed in such way that changes in the setup, like extra sensors, will not require a complete new hardware design.
27. The system must be easily connected to the other systems of E-Brake with not more than one cable for communication and power supply.
28. Apart from the sensors, the system must be implemented on only one PCB.
29. The PCB must be designed in such way that it can be used at the hitch connection as well as at the brake controller.

3

Design Process

This chapter describes the design process of the whole Hitch Connection Unit. In section 3.1, a solution is designed at system level. In the other sections this system is elaborated for each component of the system. These components will be explained in section 3.1, the system design section.

3.1 System Design

This section elaborates the design of the system at a system level and describes the different parts that are needed to achieve this system. An overview of the total HCU system is given in Figure 3.1.

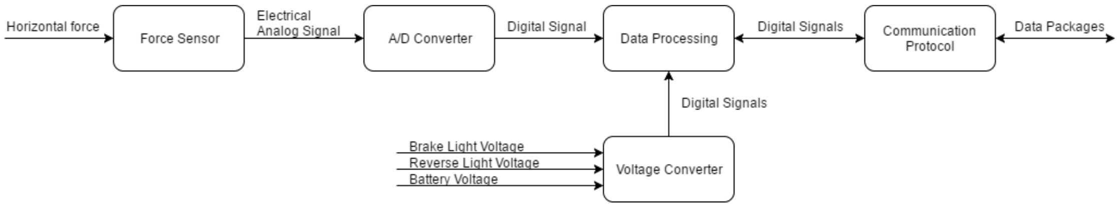

Figure 3.1: HCU total system overview

3.1.1 System Overview

The main job of the HCU is to measure the horizontal force acting between the car and the trailer and process this to the other subsystems of the brake system. To actually measure this force, a force sensor is needed. Different kind of force sensors exist and will be elaborated. Force sensors have an analog electrical signal as output which is proportional to the force exerting on the sensor. In order to process this data, it is decided to digitize this signal. Digitizing an analog signal is done using an A/D converter.

Basically, there are two ways to communicate this force to the MPU in the system. The first way is to let the MPU read out the A/D converter using the communication interface of the A/D converter. A second way is to let the HCU itself readout the A/D converter and communicate it with a different communication protocol. Letting the MPU readout the A/D converter would shift responsibility for correctly reading out the force to the MPU. For this reason it is decided to let the HCU be responsible for the readout of the A/D converter.

A requirement is that the electronic brake system on the trailer is only allowed to brake when the car itself is actually braking. There are several ways to detect this.
The first way is to monitor the communication inside the car for brake signals. Communication becomes more universal in modern cars. However, this method would still, especially for older cars, differ between different cars because of different communication protocols that still exist.

A second option is to optically sense the brake lights of the car. This however, would be difficult in different light scenes and is not recommended.
A third option is to measure the voltage of the brake lights of the trailer. Cars that can pull trailers will have a plug on the back of the car to power the lights of the trailer.
This last option is chosen because this can be uniformly implemented for all cars and it will be more robust than optically detecting the brake lights of the car. Aside from the voltage of the brake lights, the voltage of the reverse lights will be measured as well. This can be useful for the MPU to determine whether the car is driving in reverse or not at the moment the car starts to brake.

The brake system will be powered from the car battery, but an additional battery is placed inside the trailer to buffer the current drawn by the electronic brakes. The electronic brakes can draw a lot of power which will cause a reduction in the voltage of the battery. According to the requirements from chapter 2, the voltage inside the brake system needs to be at least 9.6V. Thus the voltage of this battery will be measured.

A microcontroller is needed to readout the A/D converter and to process this data. The data from the brake and reverse lights and the voltage of the battery also need processing. The microcontroller must communicate this data to other subsystems through a communication protocol.
The other modules of the E-Brake need to process and communicate data as well. In order to let all subsystems communicate with each other, a bus communication system is needed.

It is decided to implement the system on a single PCB board. This board must be connected to the other systems using cables for the bus communication.

The MPU uses the E-Connect module of E-Trailer which is part of their SMART-Trailer product [3]. This module consist of a powerful microcontroller and different sensors. The E-Connect is not suitable for the HCU, because the HCU needs different kind of sensors. The BCU, however, shows similarities with the HCU in the data processing part. For that reason the PCB designed for the HCU will be used for the BCU as well.

3.1.2 Design Synopsis

In the resting section, the elaboration of the design is divided according Figure 3.1. First the way to measure the force will be discussed in section 3.2. The characteristics for the chosen force sensor will be discussed in detail. The A/D converter part, which will digitize the analog signal from the force sensor, will be discussed in section 3.3. A suitable A/D converter is chosen and its characteristics will be discussed in detail as well. In order for the different modules of E-Brake to be able to communicate with each other, the communication protocol is described in section 3.4. The microcontroller which will process all data and maintain communication, will be addressed in the next section: section 3.5. Thereafter, in section 3.6, the converter for the car signals will be discussed. In order to tie everything together, the software for the processing part of the microcontroller will be explained in the last section of the design chapter, namely section 3.7.

3.2 Force Sensor

In this section different types of force sensors are distinguished and divided. For the chosen force sensor, its characteristics are elaborated.

3.2.1 Types of force sensors

Basically two types of force sensors can be distinguished. The first type of force sensor uses a quartz material which determines the force acting on it using the piezoelectric effect. Here the applied force to the sensor is converted to an electric charge. This charge can be measured using for example a charge-mode or voltage mode sensor system. This type of force sensors are recommended for dynamic or high speed force measurements. The second type of force sensor uses a load cell. This load cell consist of a piece of metal with strain gauges mounted on it in a Wheatstone bridge configuration. These load cells are recommended for static or quasi-dynamic force measurement and high precision. [4, Chapter 11]

A force sensor of the load cell type is chosen because of its higher precision and because the force acting on the sensor is not highly dynamic. More about the frequencies of the acting force will be discussed in section 3.3.1.

The force sensors are available in different configurations to fit different purposes. A ‘S’ type load cell is chosen because this configuration has the capability to measure tensing and compressing forces acting on it. This is needed because when driving with a car and a trailer, the sensor will be tensed during accelerating and compressed during braking. The force sensor used is the AEH3-C3-1.5t load cell [5], and will be mounted in the hitch connection of the trailer for the best measurement of the force. The indentation of the metal of the load cell is proportional to the force exerting on it. The strain gauges change in resistance value when the indentation of the metal changes. Due to the Wheatstone bridge configuration used on the load cell, the output gives a changing electrical differential signal.

The capacity, accuracy, sensitivity, and power consumption of the load cell need to be known in order to know the characteristics of the load cell. The capacity is important to specify maximum weight specifications for car and trailer to avoid overloading the load cell. The sensitivity is important for reading out the load cell correctly. The accuracy is important to state the error that is made by the HCU. The power consumption is important for the overall system to give a specification about the power that is used.

3.2.2 Capacity

For determining the capacity that the load cell should be able to handle, the maximum force on the load cell needs to be calculated. Neglecting the friction forces, the forces that act on the combination of the car and the trailer are given in Figure 3.2. To simplify the calculation, the load cell is considered as a rigid connection. This assumption can be made because the indentation of the load cell is considered to be negligible as this indentation will be in the order of micrometers. The calculation of the total brake force is given in equation 3.1.

$$F_{total} = F_{brake_{car}} + F_{brake_{trailer}} - F_{z_{\theta-car}} - F_{z_{\theta-trailer}} = (m_{car} + m_{trailer}) \cdot a_{brake} \tag{3.1}$$

For calculating the maximum force, the moment is taken when the car starts to brake but the trailer is not braking yet (i.e. $F_{brake_{trailer}} = 0$). Rewriting equation 3.1 gives an equation for the brake force of the car in equation 3.2.

$$F_{brake_{car}} = F_{z_{\theta-car}} + F_{z_{\theta-trailer}} + (m_{car} + m_{trailer}) \cdot a_{brake} \tag{3.2}$$

The resulting force on the car is given in equation 3.3.

$$F_{res_{car}} = F_{brake_{car}} - F_{z_{\theta-car}} - F_{load} = m_{car} \cdot a_{brake} \tag{3.3}$$

From the resulting force and the brake force on the car the force on the load cell can be calculated from the formula given in 3.4.

$$\begin{aligned} F_{load} &= F_{brake_{car}} - F_{z_{\theta-car}} - m_{car} \cdot a_{brake} \\ &= m_{trailer} \cdot a + F_{z_{\theta-trailer}} \\ &= m_{trailer} \cdot (a_{brake} + g \cdot sin(\theta)) \end{aligned} \tag{3.4}$$

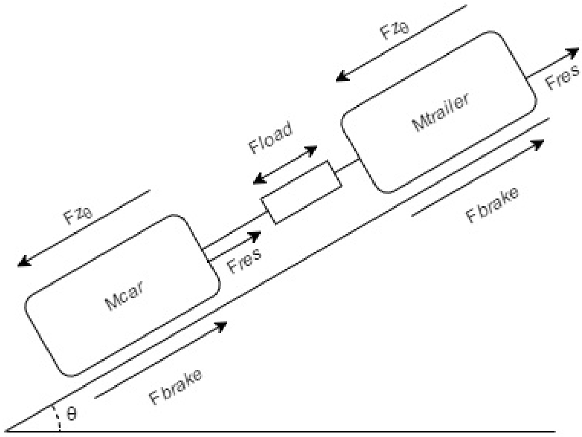

Figure 3.2: Forces on the car-trailer combination

The maximum capacity of this load cell is a force that a 1.5t mass would exert which is a force of 14.7kN. The safe overload of the load cell is 150%, which means that the load cell can handle 150% of its maximum capacity before it will deform plastically. The safe overload force is 150%·14.7kN=22.1kN. This point is defined as the yield strength of the load cell [6].
The requirement for the maximum deceleration of the trailer is given in requirement 11 in chapter 2, and is 9.8m/s^2. The maximum mass of the trailer is stated in requirement 13 in chapter 2, and is 1800kg.
The maximum slope for these requirements can be calculated with equation 3.4 and results in a slope of 14.6°.
The slope can be converted from degrees to a percentage using the equation given in 3.5 which results in a slope of 26.1%.

$$\text{Slope}_{\text{percentage}} = 100 \cdot \tan(\text{Slope}_{\text{degrees}}) \tag{3.5}$$

Because the requirement for the maximum deceleration is an extreme condition this point will not be reached often, and above all, not for a long duration. But when it will, the load cell can handle this deceleration when the mass of the trailer is within the given requirement and the slope does not exceed a rate of increase of 26.1%.

3.2.3 Accuracy

Even though that the output of the load cell is an analog electrical signal, the changes in resistances are not infinitely small. The minimal change in force that can be measured is given as v_{min}. According to the datasheet [5], the load cell has a v_{min} of 0.15kg. The characteristics in the datasheet are given as load which is the same as the force that a body with that mass would exert due to gravity acceleration. For v_{min} this is a force of 1.47N. This v_{min} is defined as “the smallest value of a quantity (mass) which may be applied to a load cell without exceeding the maximum permissible error” [6].
Other measurement errors are in the datasheet given as a combination of errors: the combined error. This combined error includes errors due to non-linearity and temperature effects [6]. The combined error is given as a maximum percentage of the full capacity and is given as 0.020%. For the given capacity of 1500kg, this yields 0.3kg or a force of 2.94N.
The load cell also has a zero balance which means that at applying no force, the load cell will not output 0V. The maximal zero balance is 1.5% of the capacity, which is 220N. This is quite a lot, but this can be compensated by calibrating the load cell and shifting this point to the point were no force is applied.

The total error of the load cell when calibrated becomes 4.41N, like stated in equation 3.6.

$$\text{Inaccuracy}_{\text{max}} = \text{Error}_{v_{min}} + \text{Error}_{\text{combined}} = 2.94N + 1.47N = 4.41N \quad (3.6)$$

3.2.4 Sensitivity

The recommended exciting voltage for the load cell is 5V to 12V [5]. Commonly the chips for the A/D converters are made to operate at 5V, so the load cell will also be excited with a voltage of 5V. The output of the load cell at the full load, is a differential voltage of 2mV per excited voltage. This means that for a voltage of 5V this will be 10mV at full load. The system is able to work at the safe overload of the load cell of 150% of the full load which gives a differential voltage of 150%·10mV=15mV. However, it must be noted that above the full load the accuracy of the load cell decreases.
The load cell measures not only compression but extension as well which gives the same differential voltage but with opposite polarity. The load cell output for a force of -22.1kN up to 22.1kN (the maximum safe load of the load cells capacity) will be -15mV up to 15mV. This gives a sensitivity of 679N/mV.

3.2.5 Power consumption

The input resistance of the load cell is 350Ω. The excited voltage of the load cell is 5V which gives a current through the load cell of 14.3mA and power consumption at 5V of 71.4mW. This is given in equation 3.7

$$I = \frac{5}{350} = 14.3mA, \qquad P = \frac{5^2}{350} = 71.4mW \quad (3.7)$$

3.3 A/D Converter

The differential voltage signals from the load cell need to be converted to a voltage signal with respect to ground so the A/D converter can refer the voltage difference of the load cell to the reference voltage. The voltage from the load cell is a small signal, as stated in section 3.2.4, so an amplifier is needed to amplify the maximum signal to the full range of the A/D converter. In a lot of A/D converter chips, especially those made for bridge measurement systems like the Wheatstone bridge, an amplifier is build inside the chip. This makes designing an amplifier itself unnecessary, however the amplification factor needs to be determined as specification for the A/D converter. Those chips that are made for bridge sensors have inputs for differential signals to a voltage with respect to ground.

3.3.1 Requirements

The A/D converter needs to have the requirements stated in this section. Important requirements are the amplification, the precision, and the sample-rate of the A/D converter.

Amplification

The excited voltage for the load cell is taken as reference for the A/D converter. As stated in section 3.2.4 the maximum output of the load cell will be between -15mV and 15mV which gives a difference of 30mV. The amplification that needs to be done is to amplify this 30mV difference to the full range of the A/D converter, which is 5V. The amplification factor needed is as given in equation 3.8 and is 166.7. The gain of the A/D converter must be as close to 166.7 but not exceeding it.

$$\text{Amplification} = \frac{V_{reference}}{V_{max}} = \frac{5}{30 \cdot 10^{-3}} = 166.7 \quad (3.8)$$

Precision

To use the accuracy possibilities of the load cell as much as possible, the A/D converter should not add much error to the total accuracy of the force measurement. This is the accuracy of the load cell added to the accuracy of the A/D converter. It is chosen that the A/D converter should have at least an 12.3-bit effective precision for adding the same maximum fault as the load cell. This is calculated by the equation given in equation 3.9, where the load cell inaccuracy of 4.41N is set as the step size error of the A/D converter. The step size error is defined as half the step size of the A/D converter.

$$\text{Precision}_{\text{effective}} = log_2(\frac{1}{2} \cdot \frac{\text{Range}_{\text{force}}}{\text{Inaccuracy}_{\text{loadcell}}}) = log_2(\frac{1}{2} \cdot \frac{2 \cdot 22 \cdot 10^3}{4.41}) = 12.3 \text{ bits} \quad (3.9)$$

Because the amplifier will not have the perfect amplification factor, a part of the possible A/D converter range will get lost. Because the precision of the A/D converter is divided over the full range, a higher precision is needed to get the same precision over the maximum range of the output of the load cell. At last, because the amplifier of the A/D converter itself will add noise, a higher bit precision will be needed to achieve at least an effective precision of 12.3 bit.

Sample-rate

The highest frequencies that are contained in physical movements of the car are around a few Hertz. This can be seen in Figure 3.3, which illustrates the force acting on the load cell in the car given in the frequency domain, during different test drives. As can be seen the most signals are located within 3Hz. To be safe, 5Hz is stated as the frequency the system should be able to measure. To measure up to this frequency the A/D converter should at least have a sampling rate (SPS) of 10Hz due to the Nyquist criterion [7]. However, a higher precision of 50-100Hz is preferred which will give the ability to mean different samples in order to filter out noise or bad samples.

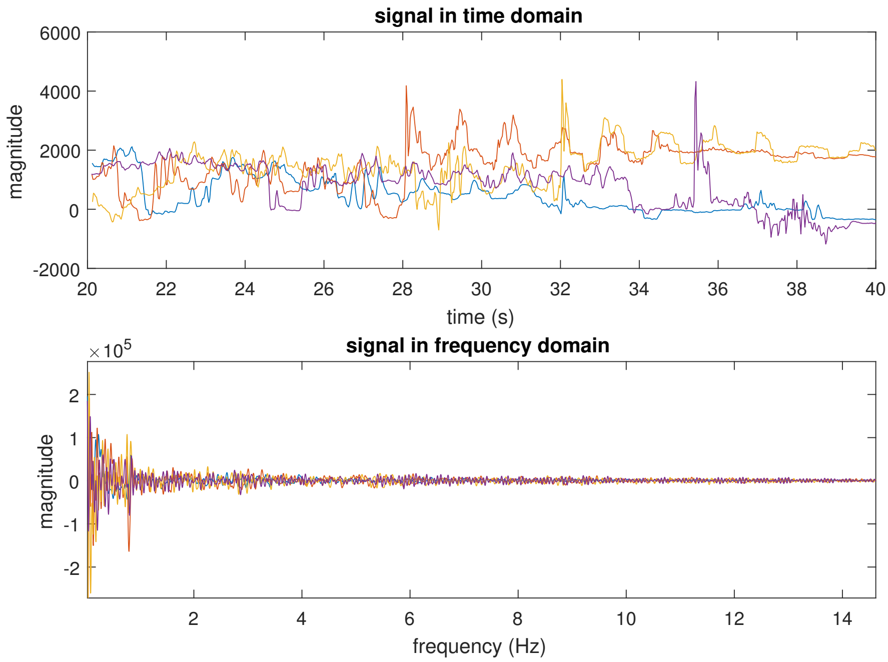

Figure 3.3: Frequency spectrum of different test rides with the load cell

As conclusion, the A/D converter should be a high precision A/D converter with a low sampling rate. The most suitable type of A/D converter for this purpose is an delta/sigma A/D converter which has high noise reduction abilities but low sampling capabilities [7].

3.3.2 Comparison

A selection of different A/D converters is made and is given in Table 3.1. The noise comparison is done by choosing a SPS between 50-100 and a gain between 100-200 if possible. In this table only A/D converter chips are taken in to consideration which are delta/sigma converters with at least 18 bits precision. They must also be suited for measuring bridge sensors.

Table 3.1: Comparison of different A/D converter chips

Name	Bit	SPS	Gain	Channels	Price (€)	DIT	RMS Noise	Peak Noise
AD7730	24	50 - 5.12k	32,64,125,250	2	20	SPI	75nV	–
AD7799	24	4,17 - 470	1 - 128	3	10	SPI	144nV	–
ADS1130/1131	18	10, 80	64	1	5	SPI	–	500nV
ADS1220	24	2000	1-128	4	8	SPI	180nV	850nV
ADS1226	24	100	–	2	7	SPI	15uV	–
ADS1230	20	10, 80	64,128	1	6	SPI	88nV	480nV
ADS1231	24	10, 80	128	1	6	SPI	102nV	622nV
ADS1232	**24**	**10, 80**	**1,2,64,128**	**2**	**9**	**SPI**	**44nV**	**247nV**
ADS1244	24	15	–	1	9	SPI	–	–
ADS1262	32	3300	1-32	4	20	SPI	58nV	352nV
HX711	24	10, 80	32, 64, 128	2	2	SPI	90nV	–
LTC2440	24	6.9 - 3.5k	–	1,2,4,8	12	SPI	510nV	–
MCP3422/3/4	18	3.75, 15, 60, 240	1, 2, 4, 8	2,4	3	I2C	1500nV	–
MCP3551	22	13.75	–	1	4	SPI	2500nV	–

The chosen A/D converter chip is the ADS1232. This is the one with the lowest noise specifications, has a gain that comes closest to the desired gain, and has a sample rate of 10 SPS with the ability of sampling with 80 SPS. This makes it possible for the processing part to mean eight samples. The A/D converter is 24-bit but gives at a gain of 128 and 80 SPS, 19.7 effective number of bits according to its datasheet [8]. Due to a lower gain, from the effective bits, just 15.2 bit-precision remains in the range of the output of the load cell. This is calculated in equation 3.10.

$$\text{Bits}_{\text{actual}} = \frac{\text{Gain}_{\text{desired}}}{\text{Gain}_{\text{actual}}} \cdot \text{Bits}_{\text{fullrange}} = \frac{128}{166.7} \cdot 19.7 = 15.2 \text{ bits} \tag{3.10}$$

This precision is more than the precision of the load cell, so the noise accuracy will not be worse than that of the load cell. The reason why this chip is also chosen above the ADS1231 is the second channel which gives the ability to include an extra sensor in the future. To measure vertical force on the hitch, add an extra load cell for making the measurement more accurate, or for reading a thermocouple for temperature measurements.

3.3.3 Anti-Aliasing filter

When performing a conversion from analog to digital, the frequency components above half the sampling frequency should be filtered to prevent aliasing. Within the amplifier an external capacitor can be connected to form a lowpass filter with an internal resistance of 2kΩ. The cutoff frequency of this filter is given by equation 3.11 and the time constant for this filter is given by equation 3.12. For a cutoff frequency f_0 of 5Hz and a resistance of 2kΩ, a capacitor of C = 15µF is needed. This filter will have a time constant of 30ms. The delay of the filter is considered as the time it takes to change 80% of its value which is 2.2·τ=66ms.

$$f_0 = \frac{1}{2\pi \cdot C \cdot R} \tag{3.11}$$

$$\tau = \frac{1}{2\pi \cdot f_0} = C \cdot R \tag{3.12}$$

3.3.4 Accuracy

Like already stated in the section 3.3.2, the effective number of bits is 15.2 on the range of the load cell. This effective number of bits is defined as the full range of the measurement divided by the RMS noise. Now the noise due to the A/D converter becomes the step size error of the effective number of bits. The maximum step size error is half the step size. The step size error of the 15.2 bits on the full range of the load cell is given in equation 3.13 and is 0.6N.

$$\text{Inaccuracy} = \frac{1}{2}\cdot\text{Stepsize} = \frac{1}{2}\cdot\frac{\text{Range}_{\text{force}}}{2^{\text{Bits}_{\text{eff}}}} = \frac{1}{2}\cdot\frac{22.1\cdot 10^{-3}\cdot 2}{2^{15.2}} = 0.6N \tag{3.13}$$

The total maximum error due to the combination of the load cell and A/D converter is the addition of the error made by both parts. This error is given by equation 3.14 and is 5N.

$$\text{Inaccuracy}_{\text{total}} = \text{Inaccuracy}_{\text{ForceSensor}} + \text{Inaccuracy}_{A/D\text{converter}} = 4.4N + 0.6N = 5N \tag{3.14}$$

3.3.5 Output characteristics

For the processing part, the digital output of the A/D converter should be converted to a force value. The derivation of the equation that relates this output to the measured force is given in equation 3.15. As can be seen, the output does not depend on the excited voltage of the load cell because this excited voltage is taken as the reference for the A/D converter. The output relates directly to the measured force, which is given in equation 3.16.

$$\begin{aligned}\text{Force} &= 0.5\cdot\frac{\text{out}}{FR}\cdot V_{ref}\cdot\frac{1}{\text{Gain}\cdot\text{Sensitivity}\cdot V_{exc}}\cdot F_{full} \quad N\\ &= 0.5\cdot\frac{\text{out}}{\text{FR}}\cdot\frac{1}{\text{Gain}\cdot\text{Sensitivity}\cdot}\cdot F_{full} \quad N\end{aligned} \tag{3.15}$$

Where:
out = signal from the A/D converter
FR = full range of the A/D converter = 2^{23}-1
V_{ref} = V_{exc} = Reference voltage of the A/D converter = Excited voltage of the A/D converter
Gain = Gain of amplifier in the A/D converter = 128
Sensitivity = Sensitivity of the load cell = 2mV/V
F_{full} = Force at full load on the load cell = 1500·9.81 = 14.1kN

$$\text{Force} = \text{out}\cdot 3.43\cdot 10^{-3} \quad N \tag{3.16}$$

3.3.6 Circuit

The circuit for the A/D converter is given in Figure 3.4. Both the analog and digital power input of the chip are powered with 5V. Close to both input power lines a capacitor is placed to filter high frequency noise. Between both 'cap' pins the anti-aliasing capacitor is placed.

3.3.7 Power Consumption

According to the datasheet the chip consumes typically 7.2mW when both the analog and digital power lines are connected to 5V and the gain is set to 128 [8]. This gives a current flow of 1.44mA which is given by equation 3.17.

$$\frac{7.2\cdot 10^{-3}}{5} = 1.44mA \tag{3.17}$$

3.4 Communication Protocol

The communication for the whole E-Brake system is based on the CAN2.0 Standard [9], because this is the most used standard in the automotive industry. This communication system is well suited for a bus

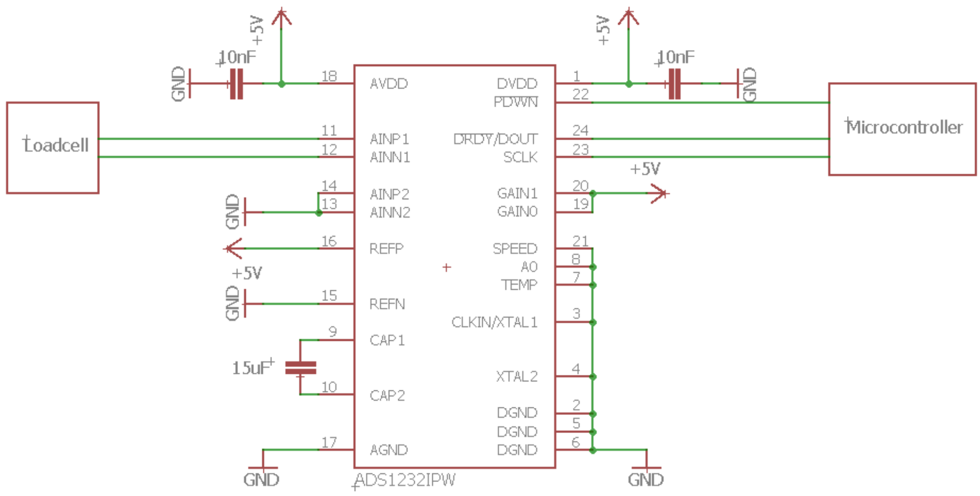

Figure 3.4: Circuit for the A/D converter

communication where a lot of different devices can be connected and can share their data. The CAN standard is a multi-master standard which means that a node, a single device, can communicate with all other nodes on the same bus. The setup of this bus can be seen in Figure 3.5. The type of message that is sent on the bus is determined by the message identifier. This identifier is part of the arbitration field in the message frame (see Figure 3.6). Message frames are broadcasted along the bus and nodes should determine individually if a message is useful for them, based on the message identifier.
An additional advantage of the CAN standard being the automotive standard is that, eventually, in the future a connection could be made between the system and the databus of the car. By connecting both systems, much more information can be shared, like accurate brake signals and brake intensity from the car, but also warnings from the trailer can be send to the car. A downside of this is that the product can influence the car. This can happen we sending data packages with the same identifiers that are already used within the system, which will cause conflicts. Because the E-Brake system will not yet be connected to the system of the car, these conflicts will not be a concern.

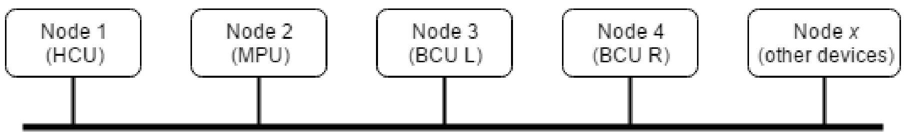

Figure 3.5: Schematic overview of different nodes connected to the same CAN bus, including what the E-Brake may look like once connected

This section will describe the use of CAN bus within the Open Systems Interconnection (OSI) model [10]. This model divides the communication system in different layers. Each layer handles a specific part of the communication like the transmissions of the bits or error detection within sending packages. This section describes the important used layers in the CAN bus, which are the physical layer and the data-link layer and gives an implementation of the application layer. It will also be discussed why other layers are not necessary.

3.4.1 Physical layer

The physical layer is responsible for converting the digital bits to electric pulses on the CAN bus wires. Like every other application, the CAN bus has its speed limits. Because it is important for the brakes to respond fast enough (within 600ms according the RDW requirements A.1), it is best to make the CAN bus as fast as possible. According to the Society of Automotive Engineers, the CAN bus in real-time control

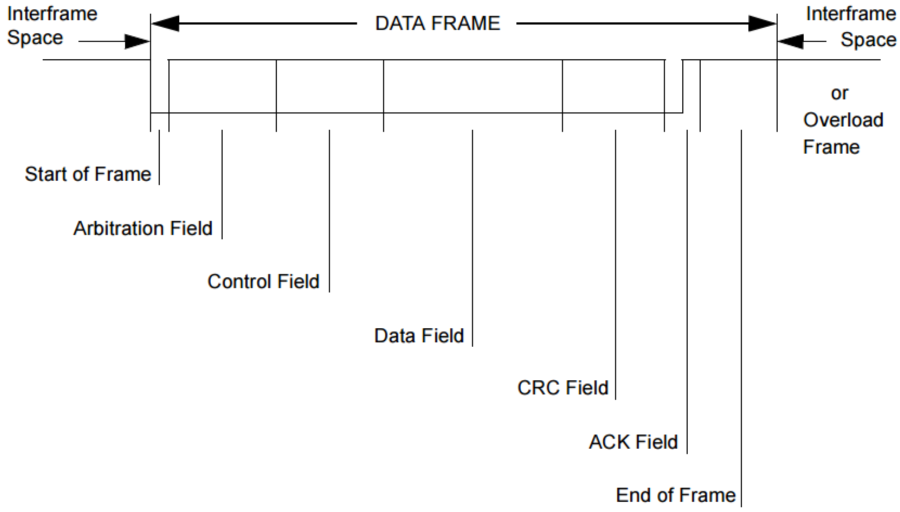

Figure 3.6: A very brief overview of a single data frame on the CAN bus [11]

systems such as ABS must have a bitrate between 125kbit/s and 1Mbit/s [12]. The CAN bus cannot handle bitrates higher than 1Mbit/s. This is due to delays of the electromagnetic waves, impedance of the line, and differences in bit timing between nodes [13].
According to table 4-11 in [13] and ISO 11898-2 [14], the length of the total CAN bus may not be longer than 40 meters if a bitrate of 1Mbit/s is used. This distance must be longer than 0.1 meter to prevent impedance mismatch in the lines between two closely placed nodes. The minimum distance between two nodes depends on the total capacitance of the nodes and the bus. Because this capacitance can very a lot due to differences in the capacitance of the nodes and of the CAN cables, it is safe to say the minimal distance must be 0.1 meter [13]. [15]
The distance from node to bus may not be longer than 0.3 meters. These lengths corresponds to the maximum limited bandwidth in the cable to achieve the given bit rate. The bandwidth is limited by electromagnetic influences and delay due to reflections in the cable.

3.4.2 Data-Link layer

The data-link layer determines the correct sending of frames over the physical layer. This is achieved using synchronization and error detection which is discussed in the next two subsections.

Synchronization and bit stuffing

The data frame of CAN (see Figure 3.6) starts with a start bit in order for all devices on the bus to synchronize their clock for the communication. To ensure this synchronization during transmission, bit stuffing is used. When five bits of the same sign are sent, an extra bit is sent with the opposite sign. This is to improve the clock synchronization. If the sixth bit is already a stuff bit, an extra stuff bit will still be needed. [16]

Error detection

The frame also consists of a CRC checksum for the receiving modules to check whether the arrived package is correct. When a single node detects a fault is sets the ACK field so the sending node knows a single node did receive the message wrong and he can send his message again.

Identifier

The data frame consists of an arbitration field, which contains the message identifier. This identifier is free to be chosen. A lower identifier has priority in the CAN protocol. In some applications for example, it will be used for addressing the different nodes.

Data field

The control field of the frame contains the length of the data field in bytes. This length can be zero up to eight bytes. The data field stores these bytes.

3.4.3 Other layers

Network Layer

The CAN standard implements no functions in the network layer of the OSI model. This is because a CAN bus is a single closed network and frames do not have to be packed in packets to be hopped between networks.

Transfer Layer

There are no functions in the transfer layer of the OSI model as well. This means that data is limited to a single data frame. This will not be a problem since the data that needs to be send will not exceed the maximum 8 bytes of a single data frame.

Session Layer

At last their are no functions in the session layer of the OSI model. The session layer is responsible to control different users on the communication interface using sessions. This is no problem because there will be constant the same devices on the bus. Because the system is closed network, no devices can connect through the network to attack devices.
There are existing protocols that can be stacked on the CAN protocol to give more control on these layers. But because the data to be send is small and fits in a single data frame and because the network is closed, no extended layers are needed.

3.4.4 Application layer

The application layer states the information that is send between nodes and assumes that the information is arrived correctly based on the lower layers. This application layer must be suitable for its application. For the communication system within the E-brake, a application layer protocol is designed.
To determine the type of data that is transmitted, the identifier in the data frame is used to indicate the priority of the message as well as the message type. The priority is useful in situations of conflict. The message type is useful for the different modules to process the data in the right way.
Because the control of the brakes is most important (to assure the brakes respond in time for safety), the corresponding brake force signals will have the highest priority. This will be a signal send from the MPU. To control the brakes, the driver must brake the car. The signal for this comes from the hitch connection unit, which gets this signal from the brake lights. This signal must also have a high priority. Because controlling the brakes (acting) is more crucial than detecting other signals (listening), the brake signal from the car will have a lower priority on the CAN bus than the brake force signals. Depending on the data type and maximum expected value of the data, the amount of bytes needed for each signal can be calculated.
The application layer describes also the way of sending data. There are two ways of sending data along the bus that are distinguished: a node can send data when they get a request for it, which is called polling. The other way is that they send data whenever they want without the need of a request, which is called pushing. Both ways have their advantages and disadvantages.

The advantages of **polling** is that data is only sent when needed (on request). When data is not needed very often, less messages will be send and thus there will be more available timeslots on the bus. Another advantage is that when a node request information from another node, it will get the most recent data.
However, disadvantages are that twice as much messages will be sent over the CAN bus. Although the request messages are very short (zero bytes of data is already sufficient), the bus will be occupied for at least 44 clock cycles [16]. The length of a data frame on the CAN bus consist of at least 44 bits. For each data byte, eight bits are added to this length. When an error is detected in the data request message frame, the whole frame needs to be resend. This causes another 44 bits of CAN bus occupation. Furthermore, if

polling is used for very important signals, like the brake signal from the car, these signals can be received (too) late.

The advantages of **pushing** is that when data is available it can be communicated directly to other nodes. All nodes will receive the most recent value of the pushing sensors. Also, there is no need for nodes to sent request messages to retrieve data from other nodes. Thus less messages will be sent over the CAN bus to retrieve data from a node. For the car brake signal it is important that other nodes receive this signal as fast as possible. In this situation, pushing works best because this method allows the signal to be transmitted almost directly to other nodes.
A disadvantage of pushing is that a node can occupy the CAN bus by constantly sending data. To prevent this, a timer can be used on each node to let the node send data on each timer interval. The data rate can be reduced even more by only sending the data values above or below a certain threshold. Using a timer will make the data less actual at the moment it is send.

The CAN2.0 standard is also chosen for future compatibility between the E-Brake and the communication network of the car. So the same communication methods for the different modules of E-Brake will be used. Most car manufactures keep this kind of information secret, but it is assumed most car sensors use the pushing method with a certain interval [17]. The pushing method is also considered as a better method for the E-Brake because of the fact that directly pushing data will give a quicker system response. This response is important in the brake system. Also, when the pushing interval match the estimated average polling (request) interval, the same data frequency is maintained but with less messages on the CAN bus. Therefore the basic setting of the sensors in the E-Brake system will be pushing.

For extended control on the CAN bus and sensors, a future version of the E-Brake system includes the possibility to configure the mode of each sensor via CAN. For the current version of the E-Brake, these settings are not yet configurable. However, the possibility to configure them is taken into account in the protocol. These settings are listed in Table 3.2. When using pushing, settings like the push interval of the sensor can be configured using the signals from Figure A.2.
Figure A.1 contains a list of all the different identifiers and their corresponding meaning in the E-Brake system. Note that the setting signals have a much lower priority than their corresponding sensor data signal. Also, a few slots are reserved and not used which means these slots can be used for future developments. Additional, some identifiers are available for error messages. Each node can use its own error identifier to send its error messages with. This can be useful to check with a CAN reader if any, and in which node, errors are occurring. The length of each data type is also visible in Figure A.1.

3.4.5 Possible Problems

The sender will know if its message has been received by all nodes on the same bus, but not whether a certain nodes handles the message. The sender will not know if its message has been handled by the right node when it needs to send a message to a particular node. However data will be send very often and if a node has no time to handle a data frame because it is busy with something, it makes more sense to receive the next, newer data frame, than to receive the old data frame again which will include a lot of overhead as well.

Table 3.2: Overview of the setting numbers with the corresponding setting

Number	Setting
1	send on request
2	send on request and on timer
3*	send on request and on timer when above threshold
4*	send on request and on timer when below threshold
5*	send on request and on timer when above absolute threshold
6*	send on request and on timer when below absolute threshold

**not supported for switching signal settings*

3.5 Microcontroller

There is still an important missing element between the sensors and the CAN bus. A microcontroller is used to read out the sensor data and prepare messages for the CAN bus. A CAN controller handles the further communication with the CAN bus. Because the bits on the CAN bus are send via differential signals, a CAN transceiver is needed to convert the data into these signals.
This section describes the choice of a micro- and CAN controller. Also, the circuit needed for the microcontroller will be discussed.

3.5.1 Requirements

The microcontroller needs to fulfill some requirements. The important requirements are given in the list below.

- The microcontroller must be able to detect the brake and reverse signals from the car immediately.
- The communication with the CAN bus must be done through a CAN controller. This can be done using a standalone CAN controller or using a build-in CAN controller.
- The speed of the CAN communication must be able to reach bit rates up to 1Mbit/s.
- To reach 1Mbit/s, the microcontroller must be able to operate at a speed high enough to handle this bit rate.
- Serial Peripheral Interface (SPI) must be available on the microcontroller in order to communicate with the A/D converter or other future sensors.
- Extra interfaces like I^2C and UART are required to be more compatible with different (future) sensors.
- The microcontroller must have an internal A/D converter to measure the voltage of the 12V supply line.
- At least three timers are needed. One timer is needed in order to use the pushing method with intervals as described in chapter 3.4. A second timer is needed to read out the A/D converter of section 3.3. The third timer is needed to output a PWM signal for the BCU.
- The microcontroller must be reprogrammable for future expansions and software updates.

A microcontroller with an integrated CAN controller is preferred for the sake of simplicity. This simplifies the control of, and the communication with, the CAN bus.

3.5.2 Comparison of available microcontrollers

There are a lot of different microcontrollers on the market. Because the system does not have to do very complicated tasks, a 8-bit microcontroller will be sufficient. Microcontrollers from ATMEL with an AVR architecture are chosen because they are the most used 8-bit microcontrollers. In Table 3.3 a common used simple microcontroller (ATMEGA328P) with external CAN controller is compared with two other microcontrollers that include a CAN controller.

Table 3.3: Comparison of different microcontrollers. The chosen microcontroller is in bold.

Name	SRAM	FLASH	SPI	I2C	Interrupts	Timers	ADC's	Price (€)
ATMEGA328P + MCP2515	2KB	32KB	yes	yes	2	2x8-bit, 1x16-bit	8x10-bit	5,-
ATMEGA32C1	2KB	32KB	yes	no	4	1x8-bit, 1x16-bit	11x10-bit	5,-
AT90CAN32	**2KB**	**32KB**	**yes**	**yes**	**8**	**2x8-bit, 2x16-bit**	**8x10-bit**	**5,-**

Detecting of the car's brake and reverse signals can be done using interrupts. The ATMEGA32C1 has got enough interrupts (at least two for the two signals coming from the car), but it does not have an I2C interface to communicate with other I2C devices. Furthermore, it has two timers which is not enough. Because the device must be compatible with a broad range of different sensors and it lacks in the amount of timers, this microcontroller will be less suitable than the other two microcontrollers.

The AT90CAN32 has almost the same features as the combination of the ATMEGA328P and MCP2515. The differences are the amount of timers, the amount of interrupts, and that the AT90CAN32 has a build in CAN controller. This build in CAN controller makes the use of an external CAN controller unnecessary. The ATMEGA328P only has two interrupts. This will be just enough for the current application, but will not support future sensors needing interrupts. The AT90CAN32, however, has got eight interrupts which is more than enough for the application.

The AT90CAN32 comes best out of the comparison and will be used and discussed further.

3.5.3 Circuit

The AT90CAN32 can operate without the need of external hardware apart from +5V supply. In order to get a higher clock frequency, a stable power supply for the chip, and to reduce noise on the measurements done by the controller, additional hardware is needed. Noise is expected in the system due to electromagnetic interference (EMI) from all kind of sources.
The final layout of the hardware for the microcontroller is given in Figure 3.7. Each of these coloured blocks will be discussed next.

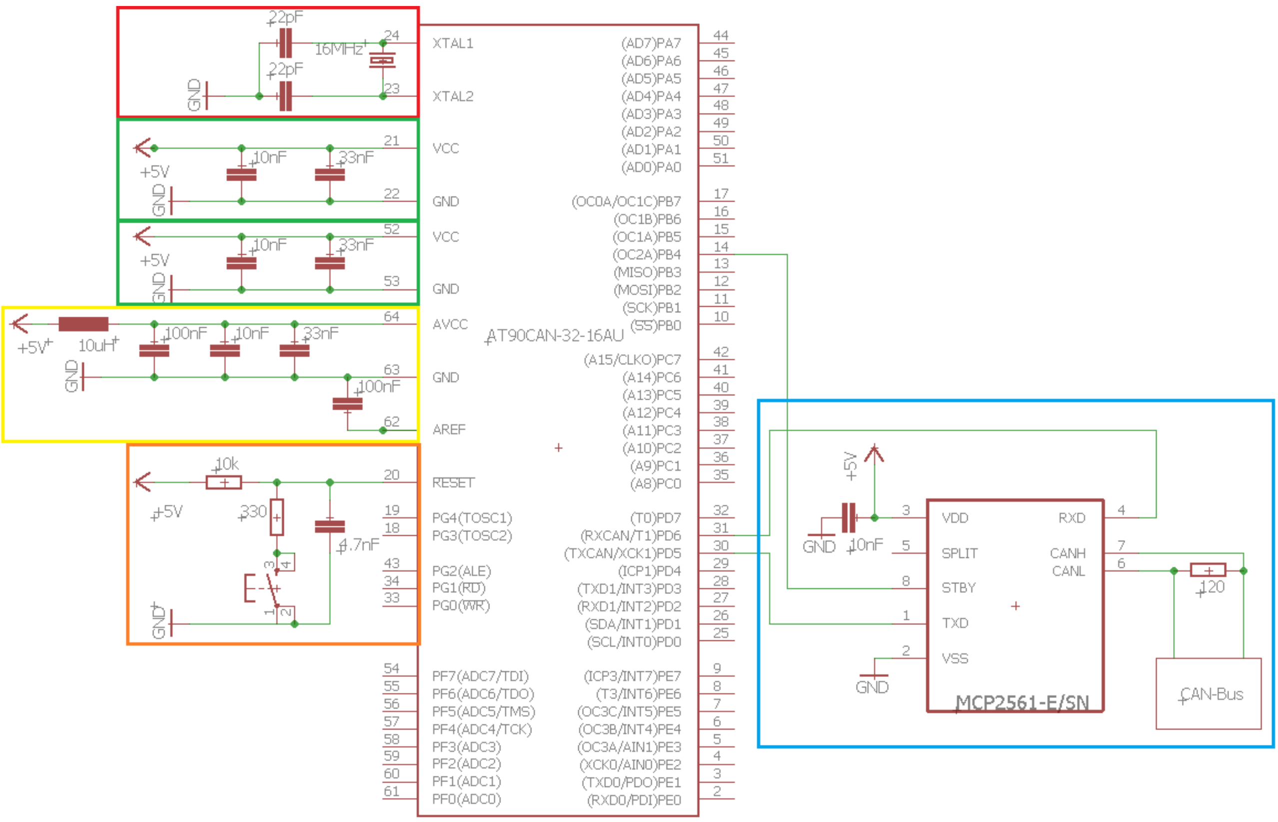

Figure 3.7: The schematic overview of the microprocessor and its connections

Clock Circuit (red)

The microcontroller (red block in Figure 3.7) needs an external crystal for a more precise clock timing. An external crystal has an typically accuracy of 20 parts per million. The internal clock of 8 MHz delivers a deviation of around 10% at a +5V supply. To get a more precise clock frequency, an external crystal is needed. The datasheet of the AT90CAN32 recommends the use of such a crystal, because the internal CAN controller needs accurate bit timing. To ensure a baud rate of 1 Mbit/s for the CAN bus, the minimum clock frequency must be 8MHz. To get the most of the speed out of the board a crystal with a clock frequency of 16MHz is used. [18]

Reset Circuit (orange)

In order to reset the microcontroller, the reset pin must be connected to ground. So during operation of the microcontroller, the reset pin must be connected to a positive voltage. The reset line has an internal pull-up resistor but if the environment is noisy, it can be insufficient. To prevent unwanted reset of the microcontroller, an extra pull-up resistor is placed on the reset pin to give it a stable positive voltage. A switch is connected to the reset to be able to reset the processor by hand. The switch is in series with a resistor to prevent unnecessary power flow [19]. Also a capacitor is connected in parallel to the switch to debounce the switch. This capacitor will catch the short voltage peaks the switch generates when it is pressed or released.

CAN Transceiver (blue)

The transceiver (MCP2561) is connected between the CAN bus and the CAN in- and output of the microcontroller. An additional wire from the transceiver to the microcontroller makes it possible for the microcontroller to completely shutdown or enable the transceiver. This may be useful for saving power.

The CAN transceiver converts the CAN signal from the microcontroller into a differential signal. This signal is outputted on its CAN high and CAN low pins. These pins are connected to the CAN bus. An additional resistor is placed parallel to these pins for termination of the bus. This termination will prevent any electromagnetic wave reflections on the bus. Therefore it is mainly used at the ends of the CAN bus. In the system of the HCU and BCU, this resistance can be decoupled when these modules are not at the end of the CAN bus.

Noise Filtering (green)

Because the internal transistors of the microcontroller switch on the clock frequency, current peaks will occur every clock cycle. These peaks must be eliminated before they reach the supply line and introduce noise in the external circuit. Eliminating this noise can be done by a simple low pass filter between the supply and ground pins of the microcontroller. This filter will also eliminate other high frequency noise.

Figure 3.8 demonstrates this principle. The introduced current peaks by the microcontroller are transmitted to the power plane. In this way, other components in the circuit which are connected to the same power plane, will also receive these unwanted current peaks. To prevent this, a filter must be implemented as close to the source of the current peaks as possible, which is between the supply and ground pin of the microcontroller. A filter must be applied between each supply and ground pin of the microcontroller to prevent unwanted current peaks in the whole circuit. As can be seen in Figure 3.8, the current peaks on the power plane are a lot smaller due to the filter.

For the supply lines, capacitors only are enough. Every power input of the chip has its own capacitor as close as possible to the pin. This in order to filter the most noise as early as possible, before it enters the power plane. The supply voltage of the internal A/D converter (yellow block in Figure 3.7) is more sensitive to the current and noise peaks because for accurate A/D conversions the voltage should be very stable. So an inductor is also coupled in series (just as can be seen in Figure 3.8) in the which will create a second order low pass filter. [20]

It is more important for these filter capacitors to have a low equivalent series resistance (ESR) than the right capacitance [20]. The noise will then be filtered much better, because the path to ground through the capacitor has a much lower resistance than the path to ground through the microcontroller. The noise chooses the path with the lowest resistance which is through the capacitor.

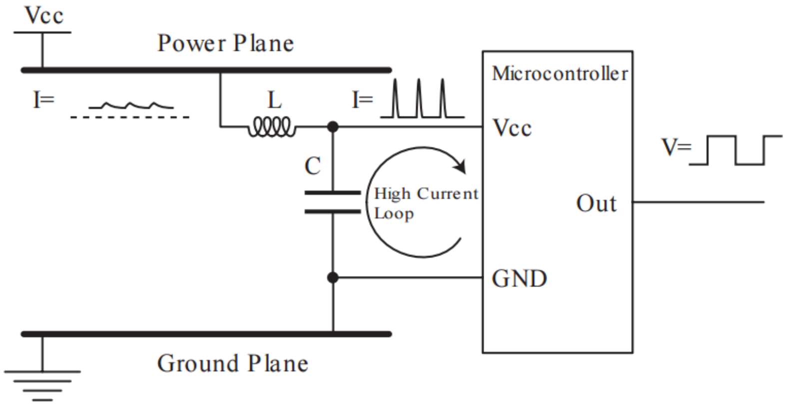

Figure 3.8: Capacitor and inductor used for decoupling at the power supply input of a microcontroller [20]

Internal A/D converter (yellow)

Also, a low pass filter must be used before feeding an analog signal to the A/D converter input. This filter must filter out all frequency components above the Nyquist frequency (= $f_{ADC}/2$) of the A/D converter. This will prevent deviant measurements caused by high frequency noise in the signal. These frequencies will be mapped to lower frequencies by the analog digital conversion, which cause deviant data. The A/D converter uses a sample and hold method, which will already eliminate a lot of higher frequency noise by averaging the signal. [18]

Other methods for preventing noise from entering the controller is keeping all loops as small as possible. For example, the external crystal must be placed as close to the corresponding microcontroller pins as possible. These small loops will reduce the amount of electromagnetic waves picked up. Also, a ground shield is needed to cover the overall system and protect it from EMI. For the clock crystal, a separate local ground plane is needed to keep the clock for the microcontroller as accurate as possible. Furthermore, it is good practice to separate analog and digital signals physically. This also accounts for high and low voltages. [20]

3.5.4 Power Consumption

The typical current consumption of the microcontroller at 5V and 16MHz is 35mA. The typical current consumption of the CAN transceiver is 5mA. When sending a high bit over the CAN bus, the current consumption can increase up to 70mA.

The load cell, A/D converter, microcontroller, and CAN transceiver all operate at 5V and consume respectively typically 14.4mA, 1.44mA, 35mA and 5mA. This results in a total typical current consumption of around 56mA at 5V.

Voltage regulator

A LM1117 voltage regulator is chosen to generate the 5V for all components. This regulator transforms an input voltage from 6.25V up to 15V to a stable 5V and can deliver up to 800mA. This is sufficient to deliver enough current to all components. A regulator dissipates the current flowing through it from input voltage to 5V as heat. So the total typical power consumption at an input of 12V will be as given in equation 3.18.

$$P = V \cdot I = 12 \cdot 56 \cdot 10^{-3} = 670mW \tag{3.18}$$

3.6 Voltage Converter

This part describes the part that measures the voltage on the powerline and that detects whether the car is braking or driving in reverse. When the car is braking or driving in reverse the car outputs a 12V signal to illuminate the corresponding lights at the back of the trailer. This signal neet to be measured to determine whether the car is braking or driving in reverse. To measure the voltage of the powerline an A/D converter is needed to digitize this analog signal. For the car signal detection digital inputs on the microcontroller are needed. Figure 3.9 contains a block diagram which shows the main principle of how these signals are converted to an digital input for the microcontroller. This diagram will be explained in the next subsections.

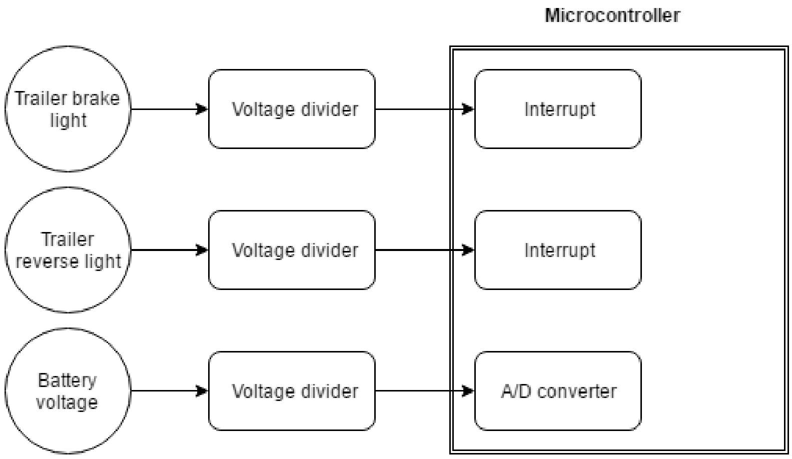

Figure 3.9: Block diagram which indicates how the signals of the car converter are routed

3.6.1 Requirements

The voltage of a car battery is typically 12V but can usually vary between a voltage of 10-14V. 15V is chosen as a maximum voltage to be measured. According to requirement 14 the system should not drop below 9.6V. To be able to measure this 9.6V, a minimum voltage to be measured is taken as 9.5V.
According to requirement 18 The indication of the car battery must be at 1 decimal precision with an accuracy of 100mV, which means that for measuring the car battery voltage, a high precision will not be needed. The state of charge of the battery does not change fast but the terminal voltage can change fast due to a fast changing power need. A sample rate of 100Hz will be sufficient to keep track of the changing terminal voltage due to changing power flow
The voltages maximum should be mapped towards a voltage of 5V, because that is the voltage the microcontroller is working at and it cannot work with higher voltages. The absolute maximum voltage on the input pins of the microcontroller may not exceed 5.5V according to the datasheet [18]. The digital pins of the microcontroller work on switching logical levels. According to the datasheet, the minimum voltage for a high level is 3V when the power of the microcontroller is 5V [18].

3.6.2 Circuit

The voltage of car battery to measured, can be measured with the internal A/D converter of the microprocessor. The microprocessor has a 10-bit A/D converter which is sufficient to obtain a precision of 0.1V. For detection of the brake and reverse signals two digital interrupt pins of the microcontroller are used. The simplest option to convert the 12V signals to 5V signals is to make a voltage division by using resistors in series. Another way would be using an operational amplifier to with an amplification smaller than 1. However, active amplification is not needed, and the amplification factor of an operational amplifier is determined by a a division using resistors as well. The internal A/D converter has a high input impedance so an operational amplifier is as well not needed as buffer.
The circuit used is given in Figure 3.10 and will be explained in the next sections.

Voltage Division

Mapping 15V to 5V gives a division ratio of 3 times. The voltage coming from the brake and reverse signal, that will be seen as a logic high will then be 3V·3=9V. This is below the minimum stated voltage that the

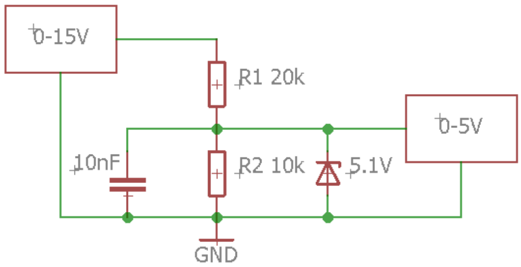

Figure 3.10: Circuit for the 12V to 5V voltage dividers

signals from the car will be. So a factor of 3 is taken for the voltage division. To achieve this ratio of 3 times, the resistors R_1 and R_2 of the voltage divider need to have a ratio of 1:2, according to equation 3.19 for the voltage at the input of the A/D converter.

$$V_{ADC} = \frac{R_2}{R_1 + R_2} V_{supply} \quad V \tag{3.19}$$

A disadvantage of the voltage division is that it continuous draws current and so consumes power. For the voltage measurement part, to prevent the voltage divider from drawing to much current, two things can be done. An electronic switch, like a transistor, could be implemented to only switch on the voltage divider when a measurement is taken. The drawback of this option is that the transistor has got an voltage drop, which makes the measurement non-linear and less accurate. A second option is to use high impedance resistors, like 1MΩ and 2MΩ. This will result in a low power consumption of 48µW at 12V, which is a negligible power consumption in comparison with the rest of the parts on the HCU.
However these higher input impedances have two drawbacks that need to be considered. First, the higher impedance resistors will also induce a larger noise voltage. But the smallest step value to be accurately measured is 0.01V, while this noise will be sufficiently lower than this step. The noise does not have a very large influence on the signal and thus these large values for the resistors are acceptable in terms of noise. A second drawback is that the internal input impedance of the A/D converter of the microcontroller is in the order of megaohms. Therefore, the voltage division, with resistors in the order of megaohms will be affected by this internal resistance. For the A/D converter resistors of a maximum order of 100kΩ are advised by the datasheet of the microcontroller. Resistors of 10kΩ and 20kΩ are used for the voltage divider circuit.

Noise Filtering

In order to filter noise at higher frequencies, a capacitor is placed in parallel to the lower resistance. This will result in a filter characteristic given in equation 3.20.

$$\frac{V_{ADC}}{V_{in}} = \frac{Z_{eq}}{R_2 + Z_{eq}} = \frac{1}{1 + \frac{R_1}{R_2} + j\frac{f}{f_0}} \qquad f_0 = \frac{1}{R_1 \cdot C \cdot 2\pi} \tag{3.20}$$

The filter goes to zero at high frequencies and keeps the same voltage division for 0Hz. Using f_0=5Hz in equation 3.20, a capacitor of 150nF is needed to filter at the Nyquist sample rate.

Input Protection

To prevent voltages higher than 5.5V at the input of the microcontroller, a zener diode is used for protection. A common value is a 5.1V zener diode which, in ideal case, cuts off the voltage at 5.1V and does not influence this voltage at lower voltages. But in practice these zener diodes will act as a resistance before reaching 5.1V. This influence needs to be validated in practice. An option can be to choose a higher valued zener diode or to place a diode with a small band gap in series with the zener diode. A second option is to give the microcontroller a look-up table for what the values should be, but this is not a very accurate option. At last it can be chosen to leave the input of the microcontroller unprotected because no voltage on the car battery are expected above the 5.5V·3=16.5V.

3.6.3 Output Characteristics

The output value of the measured voltage is given in equation 3.21. The output is dependent on the reference voltage and the division resistances. However, these factors will not be ideal which will give an inaccuracy in the measurement. This inaccuracy will be discussed in next section. When considering these factors to be ideal. The output voltage can be written as in equation 3.22.

$$\text{Voltage} = \frac{\text{out}}{FR} \cdot V_{ref} \cdot DF \quad V \tag{3.21}$$

Where:
out = signal from the A/D converter
FR = full range of the A/D converter = $2^{10} - 1$
V_{ref} = Reference voltage of the A/D converter
DF = Division Factor = 3

$$\text{Voltage} = \text{out} \cdot 14.3 \cdot 10^{-3} \quad V \tag{3.22}$$

3.6.4 Accuracy

As stated in the output characteristics the output is dependent of voltage reference and on the division factor. The used voltage regulator for 5V is the LM1117-5V. This voltage regulator has a 1% voltage accuracy, which is 0.05V. The resistances have a typical accuracy of 1%, but more precise resistors are chosen which have 0.1%, which is 10Ω for 10kΩ and 20Ω for 20kΩ. The maximum fault in the division factor will be when R_1 has a 0.1% lower resistance and R_2 a 0.1% higher resistance. This gives a fault in the division factor of 0.004. The fault in the output of the A/D converter due to this inaccuracies will be 1.15% which is given by equation 3.23.

$$\text{Inaccuracy} = \frac{\text{Fault}}{\text{Ideal}} = \frac{\text{Voltage} \cdot \frac{1}{DF_{fault}} \cdot \frac{1}{Vref_{fault}}}{\text{Voltage} \frac{1}{DF_{ideal}} \cdot \frac{1}{Vref_{ideal}}} = \frac{\text{Voltage} \cdot \frac{1}{2.996} \cdot \frac{1}{4.95}}{\text{Voltage} \cdot \frac{1}{3} \cdot \frac{1}{5}} = 1.15\% \tag{3.23}$$

Due to digitizing, the 10-bit used A/D converter from the microcontroller will give an inaccuracy in stepsize of 0.05% which is given by equation 3.24.

$$\text{Error}_{\text{stepsize}} = \frac{1}{2} \cdot \frac{1}{\text{Steps}} = \frac{1}{2^{10}} = 0.05\% \tag{3.24}$$

But the maximum fault for the A/D converter is given as 2-bits which means that the minimal accuracy is 8-bit. So the 8-bit is considered as the accurate steps of the A/D converter which gives an accuracy of 0.2% according to equation 3.24 with steps set to 2^8.
The thermal noise voltage given by equation 3.25 is considered to be sufficiently small because the bandwidth is limited to 5Hz and the resistors are not chosen high and therefore this is not taken into consideration.

$$V = \sqrt{4kTBR} \qquad [21] \tag{3.25}$$

The total inaccuracy for the measured voltage will result is equation 3.26.

$$\text{Fault}_{\text{converter}} = \text{Fault}_{\text{components}} + \text{Fault}_{\text{stepsize}} = (1.15\% + 0.2\%) \cdot V_{input} = 1.35\% \cdot V_{input} \tag{3.26}$$

According to equation 3.26, the maximum accuracy is 128mV at 9.5V and 200mV at 15V, and typical maximum accuracy of 162mV at 12V. This is not within the requirement of an accuracy of 100mV, but because the absolute maximum conditions are chosen here, the typical accuracy will be much lower. The accuracy could be improved by taking a higher precision voltage regulator which is the main cause for the inaccuracy. But these typically cannot deliver enough current for the total system. So a seperate higher precision voltage regulator could be chosen to serve as voltage reference. However that would make the system more complex and expansive so the current design is chosen.

3.6.5 Power Consumption

The maximum power consumption for the three converters when the brake and reverse signals are powered is given in equation 3.27. The power consumption is dependent on the voltage of the car battery. For the voltage range of 9.5V to 15V the power consumption will be 9mW to 22.5mW. The typical power consumption will however be at 12V with the brake and reverse signal not powered. This gives a power consumption of 4.8mW. The total typical power consumption at 12V of the HCU becomes (with the previous calculated power consumption in section 3.5.4): 672mW + 4.8mW = 677mW.

$$\text{Power} = 3 \cdot \frac{V_{in}^2}{R_1 + R_2} = 3 \cdot \frac{V_{in}^2}{30000} = \frac{V_{in}^2}{10000} \quad W \tag{3.27}$$

3.7 Processing

Processing of the data and communication is done by software on the microcontroller. This software is specifically written for the E-Brake's HCU and BCU. The software of both the modules is merged and thus the same code is available on all prototypes for the HCU and BCU. The microcontroller can switch between these codes via a dip switch on the prototype. In this section, only the code in line with this report will be discussed. That is the code of the HCU. The BCU, however, uses the same framework and methods as mentioned in this section

The code is designed to be easily modified by the programmer. This is accomplished by the use of classes and functions. These classes and functions, and also the main concept of the code, will be explained in this section.

3.7.1 Main concept

All the code is written in C++ instead of C, which is often used for programming microcontrollers. C++ gives more functionality in respect to C. C++ almost has the same functions as C but it is more flexible. Also, C++ supports the use of classes, which is used in the E-Brake for the CAN controller and the configuration class. Furthermore, namespaces can be used in C++ in order to make the code more extendable. [22]

In Figure 3.11 a flowchart of the main system is shown. Basically, in the standard operation mode, after everything is initialized the system simply waits for flags which are a sign for a certain process. These flags are set by interrupts which can come from timers, external signals or data that is ready to be processed like the A/D converter or CAN bus data. The main *while* loop will poll these flags and handles the further data processing associated with the interrupt. This type of system is called a Round-Robin system with Interrupts [23]. In this system, the interrupts have their priority and set flags. However, the handling of these flags is done with no priority. When an interrupt occurs in which a process can be done rather quickly, no flag will be set and the interrupt will handle the process.

All interrupts are shown in Figure 3.12. Each interrupt and its associated flag handle some part of the system. Some interrupts retrieve data, like the output of the A/D converter, while other interrupts are responsible for sending this data on the CAN bus.

Init

In the init functions, which are executed first, the CAN communication and the A/D converters are initialized. Also the timers are set up and the global variables are defined. These global variables will hold the

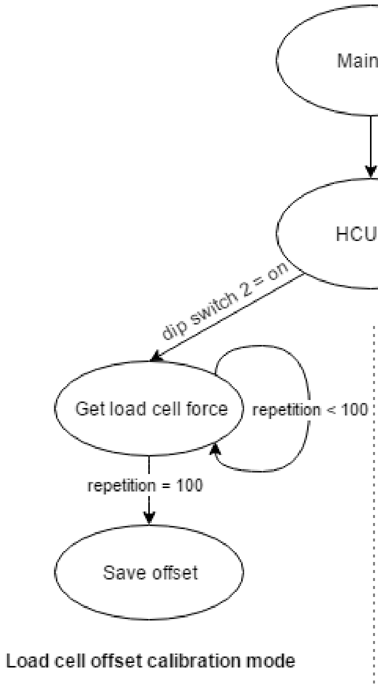

Figure 3.11: Function Structure Diagram (FSD) of the main system concept

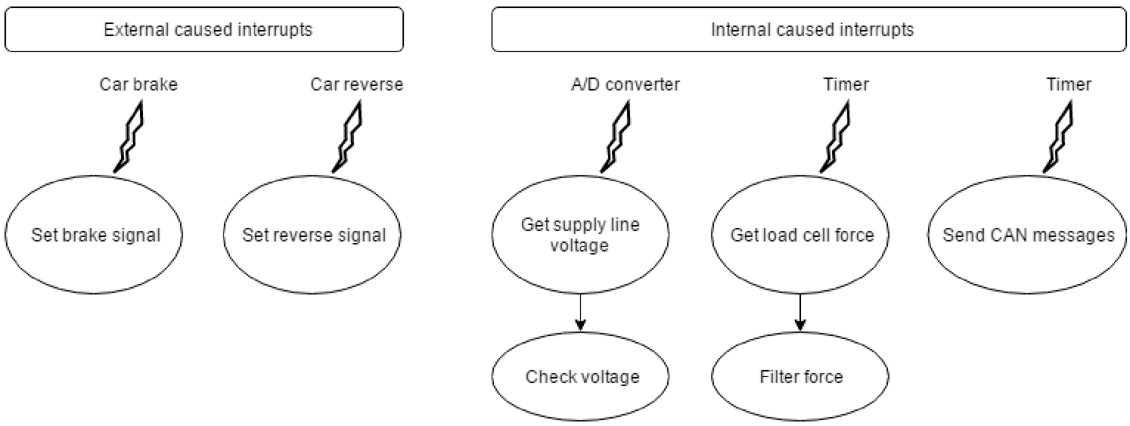

Figure 3.12: Function Structure Diagram (FSD) of the interrupts

retrieved sensor values during the whole runtime. This will ensure that this sensor data can be used always, and anywhere, in the code.

Load cell offset calibration

After the initialization, the system can run different codes. The first choice is the load cell force offset calibration. This code will measure the offset of the load cell and takes the mean of 100 samples. The trailer must not be attached to the car to ensure there are no external forces on the load cell other than the trailer itself. When the trailer is attached to the car, the car will exert a force on the trailer and thus the load cell. This force depends on all kind of parameters, like the slope on which the car and trailer combination is placed. When the mean is calculated, it will be stored in the EEPROM memory. This memory is non-volatile so the offset value will be contained even after power down of the whole system.
This load cell offset calibration should be done while installing the E-Brake system, so the end user will

not have to worry about it.

Standard operation

When the system is already calibrated for the load cell offset and the standard operation mode is selected via the dip switch, the system will retrieve the load cell offset from the memory. This will be used to correct the load cell force. The rest of the runtime, the system simply waits for interrupts to occur in order to retrieve and handle sensor data.

External caused interrupts

The brake and reverse signals from the car are connected to an interrupt pin of the microcontroller. These signals will be converted to an estimated 4V as stated in section 3.6, which will be enough to generate an interrupt. The microcontroller will set the internal brake or reverse variable to 1 or 0 during these interrupts, depending on the received signal.

Internal caused interrupts

Each time the internal A/D converter of the microcontroller has finished its conversion, it will give an interrupt. That will be the moment the converter will be read out and its data will be saved. This data will be converted to the right value which will represent the voltage of the supply line. If the voltage reaches below the required minimum of 9.6V (see chapter 2), a warning will be send over the CAN bus.
A timer is set to retrieve the load cell data once every 12.5ms. The external A/D converter operates at 80 conversions per second, so the microcontroller needs to retrieve these conversions at the same speed. When the timer is finished, an interrupt will set a flag. A flag is set because it takes time to set up the SPI interface to communicate with the A/D converter. When the flag is polled by the main *while* loop, it will read out the A/D converter.
To not overload the CAN bus the microcontroller will send sensor data with intervals. This is done with the same timer interval as the timer used for reading out the A/D converter. At each interval the measured data will be send over CAN because it is read out at that speed. This will ensure the MPU gets the most recent data at the highest rate possible. Because sending data over CAN takes some time, this is also done after a timer interrupt has set a flag.

4

Prototype and Validation

This chapter contains the implementation of the HCU and the results obtained with this implementation.

4.1 Implementation

A first implementation is done on a prototype board where the selected components with their given circuits are connected to each other. After the programming of the microcontroller and the circuit on the prototype board are tested, a PCB is designed that suits for the HCU and BCU.

4.1.1 PCB

The layout of the PCB is given in appendix A.3.1. On the PCB are 3 LED's connected to the microcontroller for debugging purposes. A 4-way DIP switch is connected to the microcontroller for configuration settings of the board. Further more, pinouts on the board are given for UART and I2C communication, PWM outputs, and for ADC inputs. A M12-5 connector is used for the cable connection with the CAN bus. A M12-8 connector is used for connections to the load cell and the car signals. Further testings were done with this PCB.

Dip switch

The microcontroller can switch between the code of the HCU and BCU via the dip switches on the PCB. In this way, one can program all the PCB's with the same code. Another advantage is that a broken PCB can be easily replaced with another PCB, without the need to know which code is on it. Via the dip switch, the PCB can be configured for each submodule: HCU, BCU on the left side, or the BCU on the right side. The microcontroller must be reset to adopt the new settings. This will prevent suddenly and unintentionally configuration changes. These settings are also shown in Table 4.1. The test mode can be modified, but for the prototype this mode acts as a CAN-to-Serial reader. Debugging the system can be turned on and off as well via a dip switch, this enables the LED's and serial output.

4.2 Results

This section describes the obtained results from the tests done with the system configured as HCU. For these tests, the hitch connection PCB is connected to the load cell on the trailer, to the signals coming from the car, and to the CAN bus. The signals from the car are extracted at the multicon plug of the trailer, which is plugged in to the rear plug of the car.

4.2.1 Load cell

For the first test, the load cell is tested with a Newton meter to see if the readings of the load cell are correct. A Newton meter is horizontally hooked on the coupling of the trailer. A constant force is exerted on this

Table 4.1: Dip switch settings. 1 means the switch is switched on.

Switch nr.	**Setting**	
1	0: HCU mode	
	1: BCU mode	
2	*HCU mode:*	*BCU mode:*
	0: Standard mode	0: Left
	1: Load cell offset calibration mode	1: Right
3	0: Debugging off	
	1: Debugging on	
4	0: Normal mode (see above)	
	1: Test mode (CAN reader)	

meter while the trailer is held still via its hand brake. Via serial communication on the HCU microcontroller the load cell force is read out. The results of this test can be found in Table A.2 and Figure 4.1.

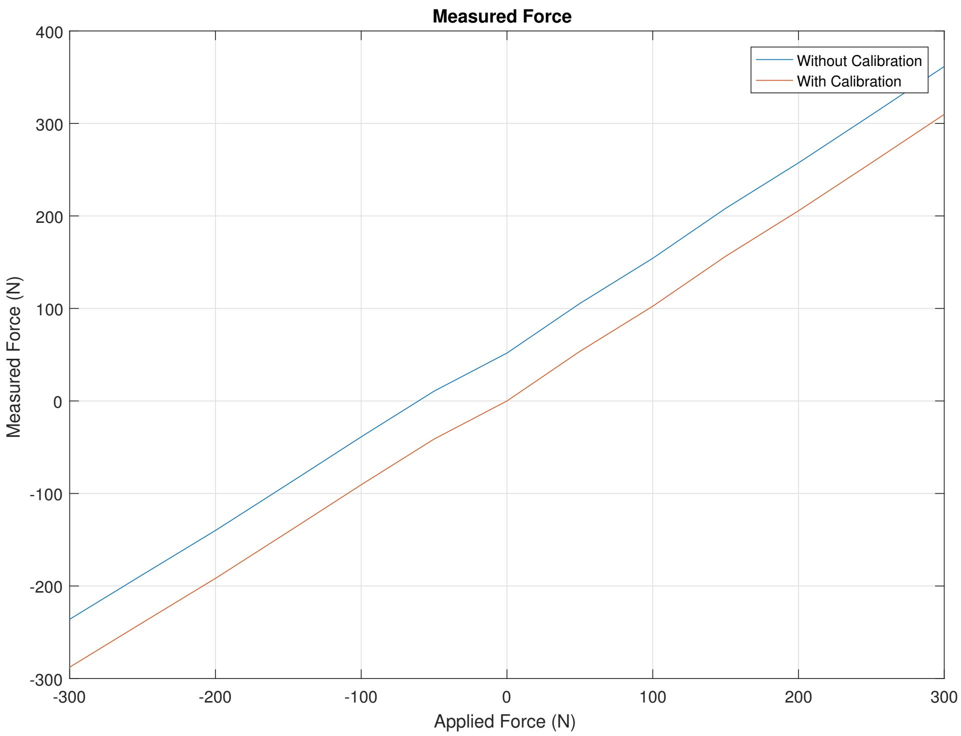

Figure 4.1: Measured force with the system using newton meter

4.2.2 Whole E-Brake system

The second, test is done by implementing the whole system in a trailer. With this trailer test rides are made at different speeds and different brake forces. Each test ride consist of an acceleration up to a certain speed (from 10km/h up to 60km/h). Once that speed is reached, the car brakes. This braking is done at different levels, like soft braking, hard braking, or cadence braking.

The HCU is mounted at the hitch connection in order to be close to the load cell. The MPU and BCU are all secured inside the trailer and also connected to the same CAN bus. The PCB's configured as brake controllers are connected to an external circuit which drives the solenoids on the brakes. Also, a camera is installed to monitor the voltage and current of the DC-DC converter which powers the external circuit of the BCU. For testing purposes, the CAN bus is connected to a stand alone battery. The DC-DC converter is also connected to two stand alone batteries in order to provide the right amount of current. This will prevent the separate systems from influencing each others supply line. However, the final product will make use of the car battery as well as an buffer battery inside the trailer. While driving with the car and trailer, the data messages on the CAN bus are logged using a CAN reader.

Force Measurement

A plot of obtained data during a test drive with no brake controllers in the brake system is given in Figure 4.2. The pulling force acting on the trailer increases when the car accelerates. In the figure this is seen as a positive increasing force. When the driver is braking, the brake signal becomes high and the force acting on the trailer changes in the opposite direction indicating a compression force on the load cell. The first brake period is during a continuous brake force exerted by the driver. During the second brake period, the driver performs cadence braking. In Figure 4.2 can be seen that the load cell force fluctuates as the brake force fluctuates.

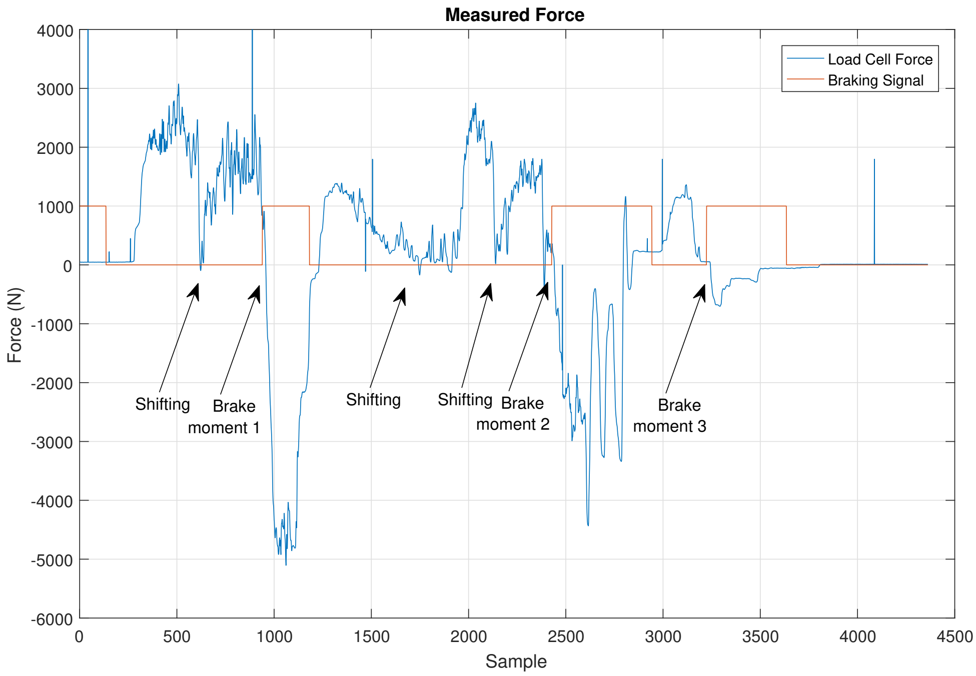

Figure 4.2: Measured force when driving with no brake controllers

Voltage Measurement

The measured voltage is validated by applying a known voltage and comparing this to the measured voltage. The voltage is measured with and without the use of a protection zener diode as described in section 3.6. The obtained results are given in Figure 4.3 and the measured voltages with its inaccuracy are given in Table A.3. As can be seen from the figure, the zener diode influences the voltage a lot when its break down voltage is almost reached.

Car Light Signals

The voltages of the light signals that are powered from the car are detected in the HCU as high signal when their voltage is 4.3V or higher with zener-diode and 4.7V or higher without zener diode. A voltage lower than this voltages or a floating signal generates a low detected signal in the HCU.

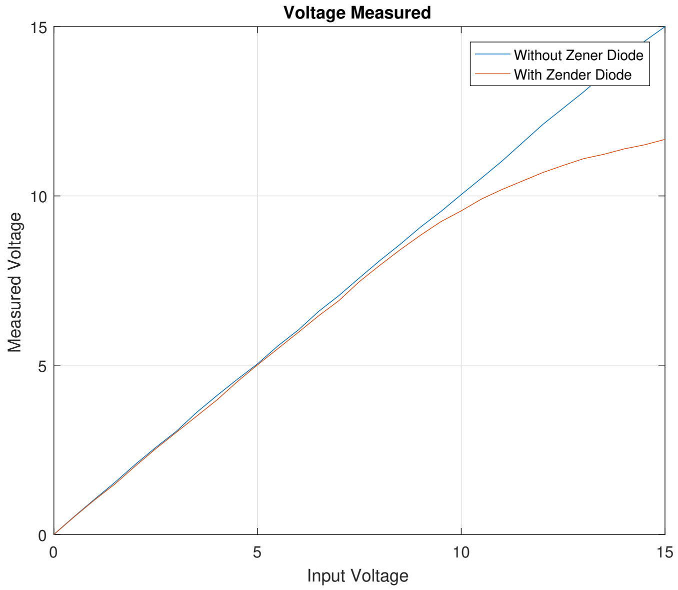

Figure 4.3: Measured voltage with respect to input voltage

Communication

To get result of the CAN communication, the PCB is also suitable as a CAN bus reader. The module sends all received CAN messages on its serial output. In this way the communication within the brake system can be logged. To test the capability of the microcontroller in correctly handling CAN messages at high speed, three HCU's are pushing messages on the CAN bus. This is done with a speed of 4 messages at 80Hz, which is 320Hz, which is the rate at which the HCU will output, as stated in section 3.7. The CAN reader logs these messages. After running one minute the CAN has received $17600 = 3 \cdot 320 \cdot 60$ messages. This means that all packages are sent and received correctly by the HCU and CAN reader. A second test is done by letting one HCU send CAN messages at the same speed as the previous test. This time the two other HCU's send back every message they get. The can reader still sees the same amount of packages on the CAN bus which means that the HCU is capable of reading and sending the messages in time.

4.2.3 Brake System

The measured force during a test drive with the full system connected (thus including the brake controllers) is given in Figure 4.4. A big difference with Figure 4.2 is that during braking the load cell force is fluctuating around zero instead of becoming a complete negative force. Also, the force does not decrease more than 400 N from the zero axis, while in the test without brake controllers the force decreased down to 5000 N.

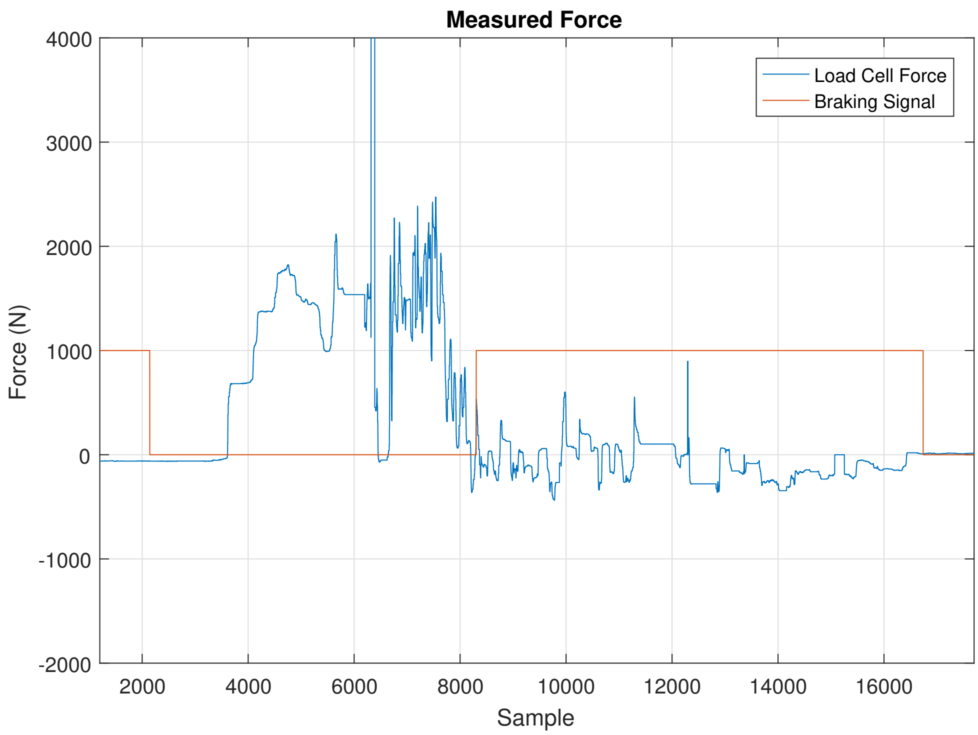

Figure 4.4: Force acting on load cell, with controlled brake system

5 Discussion

The obtained results from chapter 4 are discussed in this chapter.

5.1 PCB

The system is implemented on a single PCB which fits in an existing E-Connect casing as stated by one of the requirements of chapter 2. The dip switch does work and makes sure the right code is executed. All pinouts are also rightly connected. Only the output pins of two out of the four timers are available at a pinout. The output pin of an extra timer used for the PWM signal for the brake controllers, is not connected to a pinout although this is required to connect the PWM output to the brake controller's external circuit. Some paths on the PCB might be routed more efficiently. The path from the CAN RX pin of the microcontroller goes all the way along the edge of the PCB to the CAN transceiver. This path may be more vulnerable for receiving or generating EMI. But most paths do not contain 90 degree corners in order to reduce the EMI influences, as according to [24].

5.2 Force Measurement

5.2.1 Newton meter test

From the results of the test with only the Newton meter can be concluded that the load cell does measure the acting force on it. The used Newton meter has an accurate reading of 10N while the HCU has an theoretical accuracy of 4.41N (as stated in section 3.2.3). Further inaccuracy could be on the transmission lines from the load cell to the HCU. The inaccuracy of the measurement of the force is according to the results in table A.2 within the expected boundaries of the inaccuracy of the force measurement and that of the newton meter. Requirement 15 states that a deceleration of 0.4m/s^2 of the car has to be accurately measured. According to the formula $F = ma$, when the accuracy stays within the 20N, this would yield a minimum mass of 50kg. There are no trailers that have such low weight, so the requirement is met.

5.2.2 Whole E-Brake system test

The expected result for the force measurement is that when a car with a trailer is accelerating, the measured force will indicate a force that pulls on the trailer. When the car is braking the measured force should indicate a pushing force on the trailer, because the trailer is pushing on the car.
As can be seen from Figure 4.2 the expected results are obtained. With the car accelerating, the measured force is positive. When the car is braking, the measured force becomes negative.

5.2.3 Spikes

In the figures of the measured force, spikes can be seen which do not relate to a real force on the hitch connection. These spikes originate from a bad reading of the A/D converter. Due to a certain delay in the microcontroller, because it is busy with other tasks, a readout of the A/D converter can occur at the time the A/D converter is busy with preparing the next reading. The A/D converter and the microcontroller uses their own clocks and the A/D converter has data ready after 12.5ms. This data can be read by giving the A/D converter a serial clock tick for every 24 bit to read. A solution is to keep track of the delay between the interrupt of the timer to read out the A/D converter and the moment the flag is handled and the A/D converter is really been read. This could prevent reading at times the A/D converter is not ready for giving data. However while it is assumed the timer of the A/D converter starts at the same time the microcontroller starts, there can be a certain delay in the start up process. The timers of the both parts will have their inaccuracy as well, so these timers are not guaranteed to be synchronous after a while, which will give the same problem. A better solution is to filter out these spikes. This can be done by a digital low-pass filter which will filter these unwanted peaks.

5.2.4 Offset

As can be seen in Figure 4.2 as well, without any acceleration there is an offset in the measured force. The offset due to the zero-balance of the load cell in the force measurement part, is removed by calibrating the HCU while no car is connected. However when a car is connected, after every time driving with the car, the offset is different again. The reason for this is that when the combination of car and trailer stands still, there will still act a small force on the hitch connection. This force is too small to push the combination of the car and trailer out of each other which is due to the rolling friction of the car and the trailer. This will give no problems for the force when a car is braking while it is driving. However when the HCU is calibrated in order to shift the offset due to the zero balance of the load cell, it should be kept in mind that this must be done without a car connected to the trailer.

5.2.5 Other observations

What also can be seen is that the graph of the measured force is not a smooth curve. This is mostly because of the vibrations of the car and the trailer itself. These vibrations can be caused by the running engine of the car or simply the roughness of the road.

5.3 Voltage Measurement

The use of a protection zener diode in the voltage measurement part, influences the measurement a lot. It can be seen from Figure 4.3, that at voltages of the car battery higher than 8V, the measured voltage drops increasingly. This is due to the fact that the zener diode is not ideal and has a non-infinite resistance at voltages lower than the stated 5.1V. This resistance decreases with an increasing reverse voltage on the diode. Modelling the zener diode is a difficult task, which uses a lot of theory of semiconductor physics. An easier approach to give more accurate measurements with a zener diode is to use a look-up-table where measured voltage maps to the real voltage. However, this will decrease the accuracy of the voltage measurement and this look-up-table will be different between the zener diodes cause they have an inaccuracy within their breakdown voltage as well. It is chosen to leave out the zener diode because it is not expected to have voltages on the powerlines of the battery of the car above the maximum voltage of 16.5V. This is the maximum input voltage of the microcontroller multiplied with the conversion factor of three.

5.4 Communication

The messages of the subsystems are pushed on the CAN bus. The CAN protocol implemented in the CAN controller handles the correct transportation of messages from one system to another. The testing method described in section 4.2.2 gave the expected results. During driving there were no faults detected in the results which could be due to communication faults. The CAN bus protocol is a well suited communication protocol for the brake system and is working fine. It can be stated that due to missing network flow control in the system, it cannot be verified that a node is doing something with a certain message. If a certain subsystem crashes, it cannot process data. But the sender of the message of the message will not get awareness of the fact that a certain subsystem is not working anymore. However, every subsystem will send its data frequently. This gives the MPU the possibility to detect whether a certain subsystem is not working anymore and the user can be informed. The error messages in the protocol give the ability for subsystems to send errors when they detect faults in the system. In this way, the MPU can verify if the system is still working correctly. However it would increase the robustness and the safety of the communication if reception of the messages can be verified by the sending party.

5.5 Brake System

For the total brake system it is expected that the force measured on the hitch connection will regulate around zero which means that the trailer is braking on its own. In Figure 4.4, a plot of data of a test-drive with the full brake system can be seen where it looks like no significant force is measured on the hitch connection when braking. This means that the main processing unit controls the brake force of the brake controllers in such a way that every force acting on the hitch connection is cancelled out by letting the trailer brake on itself.

6 Conclusion

The objective stated for the total brake system was to design an innovative brake system for trailers where the pulled trailer would influence the driving experience of the driver as less as possible. The objective that is considered in this thesis was to design a system that measures the force acting between a car and a trailer, and that communicates this force to the main processing unit of the brake system.

The designed system consists of a load cell that converts a force to an electric signal by the use of a Wheatstone bridge setup with strain gauges. The conversion is done by measuring the change in resistance of the strain gauges due to the indentation. This electrical signal is amplified and converted to a digital signal by an A/D converter. A microcontroller processes and communicates this digital signal to the MPU. Communication between this subsystem and the other subsystems of the E-Brake system is done using the CAN bus protocol. Therefore a microcontroller is chosen with a CAN bus controller built in. The communication at high level is done using the designed protocol that uses unique identifiers for each type of message within the brake system. These messages are pushed frequently on the CAN bus.

Next to the force acting between the car and trailer, the voltage of the brake lights of the trailer are monitored in order to know whether the car is braking or not. This is needed because the RDW, the Dutch institute for vehicles, states the requirement that a trailer is only allowed to brake when the car is actually braking. The voltage of the reverse light on the trailer is monitored as well in order to know whether the car is driving in reverse or not, during braking. For the system to be able to validate the supply voltage of the battery of the car, this voltage is measured. These signals coming from the brake light, the reverse light, and the battery voltage are processed and pushed frequently to the other systems over the CAN bus as well.

The HCU is important in the brake system because the goal of the brake system is to get the force acting between car and trailer to zero. This indicates that the trailer brakes on itself. To accomplish this, this force needs to be known. As can be seen from the results of section 4.2.1, the system does measure the right amount of force acting on it.

The system is implemented on a single PCB and is tested while driving a car with trailer. During testing with the brakes of the trailer omitted, the force between the car and trailer increased rapidly when the car braked. When the brakes of the trailer were actively controlled by the brake controllers, the measured load cell force was correctly controlled to around 0 N. These results can be found in chapter 4.

One recommendation for further development of the HCU system, is making the system more flexible in firmware updating. At the moment, the system needs to be directly connected to a computer to upload new firmware. In the future, the system will be connected to the SMART-Trailer product of E-Trailer. This SMART-Trailer has the ability to get OTA-updates (Over-The-Air) which means that they can be updated while these systems are driving everywhere in the country. When the firmware of the HCU could be updated over the CAN bus, the SMART-Trailer system could get this update OTA and update the firmware via the CAN bus.

Another future recommendation is to be able to set system settings in the HCU via CAN. This is already implemented in the protocol, but currently not in the HCU itself. The MPU would then be able to set specific desired settings, like the send interval of the sensor data.

As final conclusion can be said that the designed HCU for the E-Brake system does fulfill the objective of this thesis. The HCU contributes to its part of the brake system by measuring and communicating the right horizontal force between the car and the trailer. This gives the brake system the possibility to regulate the force acting between car and trailer to zero by braking the trailer.

A
Appendix

A.1 Selected RDW requirements

From the list of RDW requirements for trailers [25], the most important and relevant requirements for this project are listed below. The corresponding number of each requirement is denoted between square brackets.
Chapter 5

1. The braking system shall be so designed, constructed and fitted as to enable the vehicle in normal use, despite the vibration to which it may be subjected, to comply with the provisions of this Regulation [5.1.1.1]

2. The effectiveness of the braking systems, including the electric control line, shall not be adversely affected by magnetic or electrical fields. This shall be demonstrated by compliance with Regulation No. 10, 02 series of amendments. [5.1.1.4]

3. The service braking system shall make it possible to control the movement of the vehicle and to halt it safely, speedily and effectively, whatever its speed and load, on any up or down gradient. It shall be possible to graduate this braking action. The driver shall be able to achieve this braking action from his driving seat without removing his hands from the steering control. [5.1.2.1.]

4. The power supply (generator and battery) of the power-driven vehicle shall have a sufficient capacity to provide the current for an electrical braking system. With the engine running at the idling speed recommended by the manufacturer and all electrical devices supplied by the manufacturer as standard equipment of the vehicle switched on, the voltage in the electrical lines shall at maximum current consumption of the electrical braking system (15 A) not fall below the value of 9.6 V measured at the connection. The electrical lines shall not be capable of short circuiting even when overloaded; [5.2.1.19.1]

5. In the event of a failure in the towing vehicle's service braking system, where that system consists of at least two independent parts, the part or parts not affected by the failure should be capable of partially or fully actuating the brakes of the trailer; [5.2.1.19.2]

6. The use of the stop-lamp switch and circuit for actuating the electrical braking system is permissible only if the actuating line is connected in parallel with the stop-lamp and the existing stop-lamp switch and circuit are capable of taking the extra load. [5.2.1.19.3]

7. Compensation by the electric control transmission for deterioration or defect within the braking system shall be indicated to the driver by means of the separate yellow optical warning signal specified in paragraph 5.2.1.29.2. This requirement shall apply for all conditions of loading when compensation exceeds the following limits: [5.2.2.5.1.]

8. Malfunctions of the electric control transmission shall not apply the brakes contrary to the driver's intentions. [5.2.2.6.]

9. In the case of a single temporary failure (< 40 ms) within the electric control transmission, excluding its energy supply, (e.g. non-transmitted signal or data error) there shall be no distinguishable effect on the service braking performance. [5.2.2.15.1.]

10. In the case of a failure within the electric control transmission14 (e.g. breakage, disconnection), a braking performance of at least 30 per cent of the prescribed performance for the service braking system of the relevant trailer shall be maintained. For trailers, electrically connected via an electric control line only, according to paragraph 5.1.3.1.3., and fulfilling 5.2.1.18.4.2. with the performance prescribed in paragraph 3.3. of Annex 4 to this Regulation, it is sufficient that the provisions of paragraph 5.2.1.27.10. are invoked, when a braking performance of at least 30 per cent of the prescribed performance for the service braking system of the trailer can no longer be ensured, by either providing the "supply line braking request" signal via the data communication part of the electric control line or by the continuous absence of this data communication. [5.2.2.15.2.]

11. When the supply voltage to the trailer falls below a value nominated by the manufacturer at which the prescribed service braking performance can no longer be guaranteed, the separate yellow warning signal specified in paragraph 5.2.1.29.2. shall be activated via pin 5 of the ISO 7638:200317 connector. In addition, trailers equipped with an electrical control line, when electrically connected to a towing vehicle with an electric control line, shall provide the failure information for actuation of the red warning signal specified in paragraph 5.2.1.29.2.1. via the data communication part of the electric control line. [5.2.2.20]

12. In the case of trailers equipped with an electric control line the message "illuminate stop lamps" shall not be transmitted by the trailer via the electrical control line during "selective braking" initiated by the trailer. 19 [5.2.2.22.2]

Annex 4

13. The brakes shall be cold; a brake is deemed to be cold when the temperature measured on the disc or on the outside of the drum is below 100 °C. [1.4.1.1.]

14. In an emergency manoeuvre, the time elapsing between the moment when the control device begins to be actuated and the moment when the braking force on the least favourably placed axle reaches the level corresponding to the prescribed performance shall not exceed 0.6 second. [4.1.1.]

Annex 14

15. For the purposes of the following provisions electrical braking systems are service braking systems consisting of a control device, an electromechanical transmission device, and friction brakes. The electrical control device regulating the voltage for the trailer shall be situated on the trailer. [1.2.]

16. Electrical braking systems shall be actuated by operating the service braking system of the towing vehicle. [1.3.]

17. The nominal voltage rating shall be 12 V. [1.4.]

18. The maximum current consumption shall not exceed 15 A. [1.5.]

19. A tell-tale shall be provided at the control device, lighting up at any brake application and indicating the proper functioning of the trailer electrical braking system. [2.7.]

20. Electrical braking systems shall respond at a deceleration of the tractor/trailer combination of not more than 0.4 m/s2. [3.1.]

21. The prescribed braking force of the trailer of at least 50 per cent of the maximum total axle load shall be attained - with maximum mass - in the case of a mean fully developed deceleration of the tractor/trailer combination of not more than 5.9 m/s2 with single-axle trailers and of not more than 5.6 m/s2 with multi-axle trailers. Trailers with close-coupled axles where the axle spread is less than 1 m are also considered as single-axle trailers within the meaning of this provision. Moreover, the limits as defined in the appendix to this annex shall be observed. If the braking force is regulated in steps, they shall lie within the range shown in the appendix to this annex. [3.4.]

A.2 CAN protocol

ID (dec)	ID (bit)	Family (dec)	Name	Type of Data	Data length
0	0000000000	0	Braking Force for All Brakes	Force (N)	4
1	0000000001	0	Braking Force for Brake L	Force (N)	4
2	0000000010	0	Braking Force for Brake R	Force (N)	4
3-16		0	*Reserved for future main processing commands*		
			SENSORS		
17	0000010001	1	Braking Signal	High / Low	1
18	0000010010	1	Reverse Signal	High / Low	1
19	0000010011	1	Detected Horizontal Force	Force (N)	3
20	0000010100	1	Measured Voltage	Voltage (V)	2
21-31		1	*Reserved for future hitch connection data*		
32	0000100000	2	Temperature Brake L.1	Degrees (°C)	2
33	0000100001	2	Temperature Brake L.2	Degrees (°C)	2
34	0000100010	2	Temperature Brake L.3	Degrees (°C)	2
35	0000100011	2	Temperature Brake L.4	Degrees (°C)	2
36	0000100100	2	Temperature Brake R.1	Degrees (°C)	2
37	0000100101	2	Temperature Brake R.2	Degrees (°C)	2
38	0000100110	2	Temperature Brake R.3	Degrees (°C)	2
39	0000100111	2	Temperature Brake R.4	Degrees (°C)	2
38-47		2	*Reserved for future brake temperature data*		
49	0000110001	3	Rotary Speed Brake L	RPM	2
50	0000110010	3	Rotary Speed Brake R	RPM	2
50-63		3	*Reserved for future brake sensor data*		
64-271		*4-18*	*Reserved for future modules*		

Figure A.1: Overview of the different priorities/identifiers for each signal.

ID (dec)	ID (bit)	Family (dec)	Name	Type of Data	Data length
			SETTINGS		
272	0100010000	19	Braking Sign Broadcast	Settings Type 2	1
273	0100010001	19	Braking Sign Broadcast	Time (ms)	2
274		19	*Not used*		
275	0100010011	19	Reverse Sign Broadcast	Settings Type 2	1
276	0100010100	19	Reverse Sign Broadcast	Data Timer (ms)	2
277		19	*Not used*		
278	0100010110	19	Force Detection Broadcast	Settings Type 1	1
279	0100010111	19	Force Detection Broadcast	Time (ms)	2
280	0100011000	19	Force Detection Broadcast	Threshold	3
281		19	*Not used*		
282	0100011010	19	Voltage Broadcast	Data Setting	1
283	0100011011	19	Voltage Broadcast	Data Timer (ms)	2
284	0100011100	19	Voltage Broadcast	Data Threshold (V)	2
285		19	*Not used*		
288	0100100000	20	Brake Temperature 1	Data Setting	1
289	0100100001	20	Brake Temperature 1	Data Timer (ms)	2
290	0100100010	20	Brake Temperature 1	Data Threshold (°C)	2
291		20	*Not used*		
292	0100100100	20	Brake Temperature 2	Data Setting	1
293	0100100101	20	Brake Temperature 2	Data Timer (ms)	2
294	0100100110	20	Brake Temperature 2	Data Threshold (°C)	2
295		20	*Not used*		
296	0100101000	20	Brake Temperature 3	Data Setting	1
297	0100101001	20	Brake Temperature 3	Data Timer (ms)	2
298	0100101010	20	Brake Temperature 3	Data Threshold (°C)	2
299		20	*Not used*		
300	0100101100	20	Brake Temperature 4	Data Setting	1
301	0100101101	20	Brake Temperature 4	Data Timer (ms)	2
302	0100101110	20	Brake Temperature 4	Data Threshold (°C)	2
303	0100101111	20	*Not used*		
304	0100110000	21	Wheel Speed Broadcast	Settings Type	1
305	0100110001	21	Wheel Speed Broadcast	Data Timer (ms)	2
306	0100110010	21	Wheel Speed Broadcast	Data Threshold (rpm)	2
			ERRORS		
513	1000000001	32	Error messages HCU		2
514	1000000010	32	Error messages BCU L		2
515	1000000011	32	Error messages BCU R		2
516	1000000100	32	Error messages MPU		2

Figure A.2: Overview of the different priorities/identifiers for each signal *(continued)*.

A.3 PCB

A.3.1 Layout

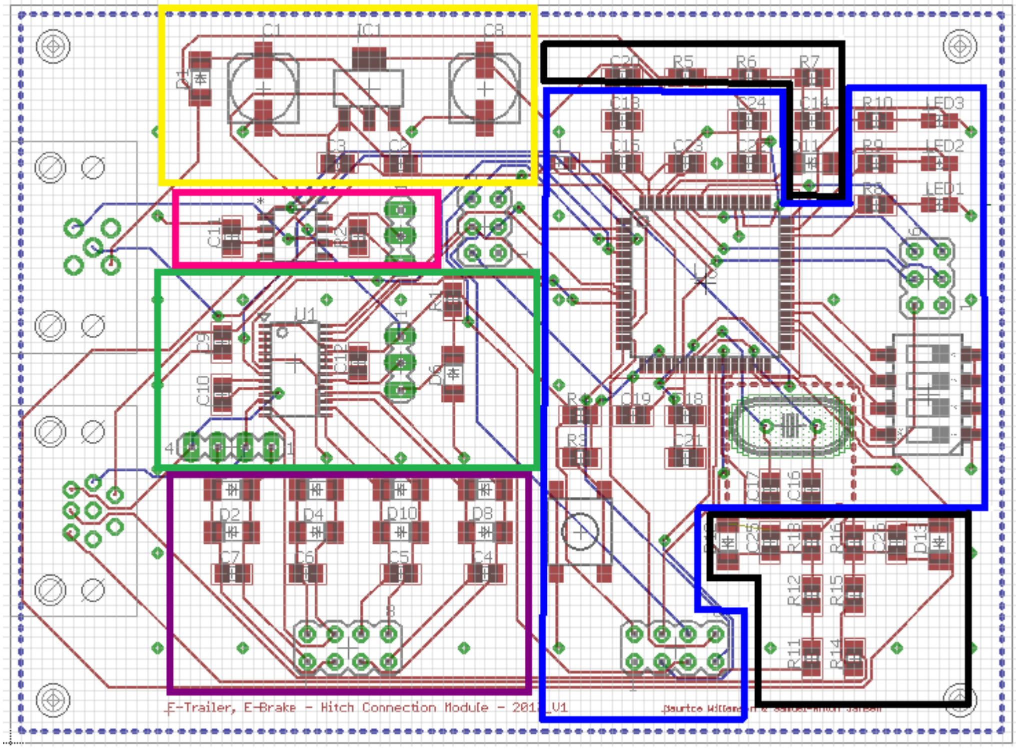

Figure A.3: Board Layout for PCB. Yellow: Power Part. Pink: CAN-Transceiver. Green: A/D Converter. Purple: Thermocouples Connections(BCU). Black: Car Signal Converters. Blue: Microcontroller part.

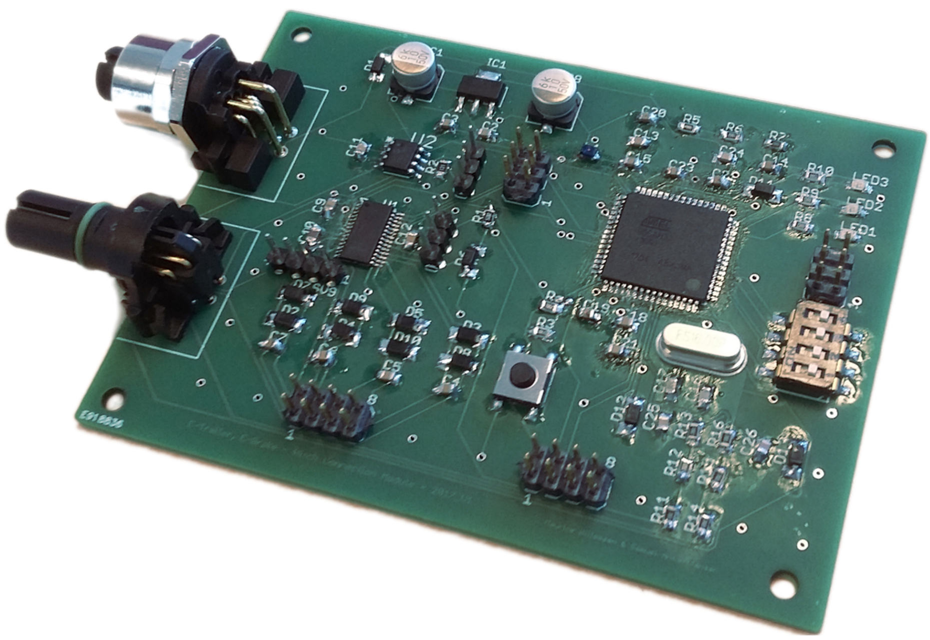

Figure A.4: Assembled PCB

A.3.2 Pinouts

Table A.1: All pinouts of the PCB

SV2 - Temperature sensors	
1	Temperature sensor 1 +
2	Temperature sensor 2 +
3	Temperature sensor 1 -
4	Temperature sensor 2 -
5	Temperature sensor 3 +
6	Temperature sensor 4 +
7	Temperature sensor 3 -
8	Temperature sensor 4 -

SV3 - External A/D converter reference voltage	
1-2	5V
2-3	2.5V

	SV5 - CAN termination resistor
1-2	Not connected to the bus
2-3	Connected to the bus

SV6 - Internal A/D converters	
1	Gnd
2	5V
3	A/D converter 2 (current sensor -)
4	A/D converter 1 (voltage sensor)
5	A/D converter 4 (speed sensor)
6	A/D converter 3 (current sensor +)

SV7 - Programmer	
1	Gnd
2	Reset
3	RX (Serial)
4	SCK (clock)
5	5V
6	TX (Serial)

SV8	
1	Gnd
2	5V
3	I2C
4	I2C
5	TX (Serial)
6	RX (Serial)
7	Timer1A
8	Timer1B

SV9 - Switch load cell / temperature sensor	
1-2 & 3-4	Temperature sensor
not connected	Load cell

5-pole CAN connector	
1	Gnd
2	CAN High
3	Gnd
4	12V
5	CAN Low

8-pole CAN connector	
1	5V
2	Gnd
3	Gnd
4	Reverse Signal
5	Brake Signal
6	Load cell +
7	Load cell -
8	Gnd

A.4 Results

A.4.1 Force Measurement

Table A.2: Force measurements of the load cell

Applied Force (N)	Measured Force 1 (N)	Measured Force 2 (N)	Measured Force 3 (N)	Measured Force 4 (N)	Measured Force 5 (N)	Mean Measured Force (N)	Calibrated Measured Force (N)	Difference with applied force(N)
-300	-235	-238	-237	-234	-236	-236	-287,8	12,2
-250	-187	-186	-185	-190	-191	-187,8	-239,6	10,4
-200	-140	-140	-140	-140	-140	-140	-191,8	8,2
-150	-88	-89	-90	-92	-89	-89,6	-141,4	8,6
-100	-40	-38	-41	-37	-38	-38,8	-90,6	9,4
-50	9	12	13	8	11	10,6	-41,2	8,8
0	54	53	51	52	49	51,8	0	0
50	108	106	103	106	104	105,4	53,6	3,6
100	156	153	155	153	154	154,2	102,4	2,4
150	207	210	209	207	208	208,2	156,4	6,4
200	258	259	254	257	259	257,4	205,6	5,6
250	309	311	308	312	306	309,2	257,4	7,4
300	362	362	359	361	364	361,6	309,8	9,8

A.4.2 Voltage Measurement

Table A.3: Voltage measurements and comparison with and without the use of a zener diode

Aplied Voltage (V)	Measured Voltage Without Zener Diode (V)	Measured Voltage with Zener Diode (V)	Inaccuracy without Zener Diode (mV)	Inaccuracy with Zener Diode (mV)
0	0	0	0	0
0,5	0,53	0,52	30	20
1	1,04	1,02	40	20
1,5	1,54	1,49	40	-10
2	2,07	2,02	70	20
2,5	2,57	2,53	70	30
3	3,04	3,01	40	10
3,5	3,6	3,49	100	-10
4	4,1	3,97	100	-30
4,5	4,58	4,51	80	10
5	5,04	5,01	40	10
5,5	5,57	5,49	70	-10
6	6,04	5,97	40	-30
6,5	6,59	6,46	90	-40
7	7,06	6,91	60	-90
7,5	7,58	7,47	80	-30
8	8,09	7,95	90	-50
8,5	8,57	8,41	70	-90
9	9,08	8,84	80	-160
9,5	9,54	9,24	40	-260
10	10,04	9,56	40	-440
10,5	10,53	9,91	30	-590
11	11,03	10,19	30	-810
11,5	11,57	10,44	70	-1060
12	12,11	10,69	110	-1310
12,5	12,59	10,9	90	-1600
13	13,07	11,1	70	-1900
13,5	13,59	11,23	90	-2270
14	14,08	11,39	80	-2610
14,5	14,57	11,51	70	-2990
15	15	11,67	0	-3330

Bibliography

[1] etrailer. (2016) Trailer brake controller information | etrailer.com. [Online]. Available: https://www.etrailer.com/faq-brakecontroller.aspx

[2] N. Kudarauskas, "Analysis of emergency braking of a vehicle," *Transport*, vol. 22, no. 3, January 2007.

[3] E-Trailer. (2016) Smart-trailer. [Online]. Available: http://e-trailer.nl/producten/smart-trailer/

[4] J. S. Wilson, *Sensor Technology Handbook*. Elsevier Inc., 2005.

[5] *AEH3 S type loadcell*, AE sensors, December 2013.

[6] P. Zecchin, "Loadcell accuracy in process weighing," *Sensor Review*, vol. 13, no. 3, pp. 9–12, 1993.

[7] S. Ball. (2001, Januari) Analog-to-digital converters. [Online]. Available: http://www.eetimes.com/document.asp?doc_id=1276974

[8] *24-Bit Analog-to-Digital Converter For Bridge Sensors*, Sbas350f ed., Texas Instruments, June 2005. [Online]. Available: http://www.ti.com/lit/ds/symlink/ads1232.pdf

[9] J. Schambach, L. Bridges, W. Burton, G. Eppley, K. Kajimoto, and T. Nussbaum, *CANbus protocol and applications for STAR TOF Control*, Physics Department, University of Texas at Austin, 2011.

[10] P. van Mieghem, *Data Communications Networking*, 2007.

[11] *CAN Specification*, Robert Bosch GmbH, 1991.

[12] G. Leen, D. Heffernan, and A. Dunne, *Digital networks in the automotive vehicle*, Department of Electronic Control Engineering, University of Limerick.

[13] I. de Gijsel, *CAN en EOBD*. Elektor International Media BV, 2009.

[14] ISO, *ISO 11898-2:2003: Road vehicles – Controller area network (CAN) – Part 2: High-speed medium access unit*, International Organization for Standardization, 2003.

[15] S. Corrigan, "Controller area network physical layer requirements," Texas Instruments, Texas Instruments, Post Office Box 655303, Dallas, Texas 75265, Application Report SLLA270, January 2008.

[16] K. Pazul, *Controller Area Network (CAN) Basics*, Microchip Technology Inc., 2002.

[17] B. Negley. (2000, October) Getting control through can. [Online]. Available: http://www.sensorsmag.com/iot-wireless/getting-control-through-can

[18] *Microcontroller with 32K/64K/128K Bytes of ISP Flash and CAN Controller*, Atmel Corporation, 2325 Orchard Parkway, San Jose, CA 95131, USA, 2008.

[19] *AVR042: AVR Hardware Design Considerations*, Atmel Corporation, 1600 Technology Drive, San Jose, CA 95110 USA, 2016.

[20] *AVR040: EMC Design Considerations*, Atmel Corporation, 1600 Technology Drive, San Jose, CA 95110 USA, 2016.

[21] P. Regtien, *Electronic Instrumentation*. VSSD, 2005.

[22] cs Fundamentals.comr. (2016) Difference between c and c++ with example. c vs c++. [Online]. Available: http://cs-fundamentals.com/tech-interview/c/difference-between-c-and-cpp.php

[23] D. E. Simon, *An Embedded Software Primer*. Pearson Education, 1999.

[24] Y. Chen, G. Chen, and K. Smedley, “Analysis and measurement of small inductance of loops and vias on printed circuit board,” in *Industrial Electronics Society, 2003. IECON ’03. The 29th Annual Conference of the IEEE*, vol. 2, Nov 2003, pp. 1661–1666 Vol.2.

[25] “Addendum 12: Regulation no. 13,” March 2014.