Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Analysis and Design of a Redundant X-by-Wire Control System Implemented on the Volvo Sirius 2001 Concept Car

Examensarbete utfört i Reglerteknik
vid Tekniska högskolan i Linköping
av

Pär Degerman & Niclas Wiker

LiTH-ISY-EX-3365-2003

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Titel
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Analys och design av ett redundant x-by-wire kontrollsystem till Volvos konceptbil Sirius 2001

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Författare
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Sammanfattning
Abstract

The purpose of this master thesis project has been to analyze and document the Sirius 2001 Concept Car. In addition, it has also been a goal to get the car in a usable state by implementing new software on the on board computers.

The car is a Tiger Cat E1 that is modified with four wheel steering and an advanced X-by-Wire system. The computers in the X-by-Wire system consist of six TTP PowerNodes that communicate with each other over a redundant, fault tolerant TTP/C communications bus. The computers are connected to a number of sensors and actuators to be able to control the car.

This project has contributed to the car in several ways. A complete documentation of the systems implemented in the car is one. Another is a programmers manual which significantly lowers the threshold when working with the car. Last but not least is the modifications in hardware and software, which have made the car usable and show some of the possibilities with the system.

The results show that the Sirius 2001 Concept Car is a suitable platform for research in car dynamics and fault tolerant systems. The work has also shown that the TTP/C communication model works well in an application like this.

Nyckelord
Keywords X-by-Wire, Steer-by-Wire, Brake-by-Wire, Redundant, TTP/C, Concept Car

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Sammanfattning

Syftet med det här examensarbetet är att analysera och dokumentera konceptbilen Sirius 2001. Ett annat mål har varit att implementera ny mjukvara i bilens datorer för att på så sätt kunna göra bilen användbar.

Bilen är en Tiger Cat E1 som är modifierad så att den är fyrhjulsstyrd och använder sig av ett avancerat x-by-wire-system. Datorerna som bygger upp x-by-wire-systemet är sex stycken TTP PowerNode som kommunicerar med varandra över ett feltolerant och redundant TTP/C-nätverk. Datorerna är också anslutna till ett antal sensorer och aktuatorer för att kunna kontrollera bilen.

Projektet har bidragit till bilen på flera sätt. Ett är den kompletta dokumentationen över de olika systemen i bilen, ett annat är en programmeringsmanual som betydligt sänker inlärningströskeln för vidare projekt. Slutligen har flera förändringar i både hård- och mjukvara förbättrat bilens användbarhet och belyser en del av de möjligheter som erbjuds i ett system av den här typen.

Resultaten visar att konceptbilen Sirius 2001 har stor potential som en plattform för ytterligare förskning inom områdena fordonsdynamik och feltoleranta system. Vidare har också TTP/C-protokollet visat sig motsvara de krav som ställs i x-by-wire-system.

Preface

This Master Thesis project was initiated in the beginning of September 2002, and this report is the result after its almost 24 week duration.

The project has been carried out at the Department of Mechanical Engineering (IKP), Linköpings universitet. However, the authors has also registered the project at the Department of Electrical Engineering (ISY), and as a consequence, two versions of the report is found. Still, except for the title page, their contents are the same.

Together with the report, a CD-ROM has been included. It contains valuable information for anyone with the intention to continue to work with the system. Among the included substance are hardware specification sheets and programming code.

The entire report has been created using the $\LaTeX\,2_\varepsilon$ package.

Pär Degerman, Applied Physics and Electrical Engineering program
Niclas Wiker, Mechanical Engineering program
Linköping, march 2003

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Also worth mentioning are our opponents, *Jonas Elvfing* and *Mikael Littman*, who have provided us with suggestions on the content, as well as the structure of the report.

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- *Sören Hoff*, also at the University workshop, for helping us with the manufacturing of circuit boards.
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And Niclas would like to thank *Ulf Bengtsson* at IKP, for tips on handling the Pro/ENGINEER software package.

Abbreviations

ABS	Anti Blocking System
BDM	Background Debugger Mode
CAN	Controller Area Network
CL	Center Left Node
CR	Center Right Node
DC	Direct Current
DSTC	Dynamic Stability and Traction Control
FL	Front Left Node
FR	Front Right Node
GND	Ground
hp	Horsepower
I/O	Input/Output
inc/rev	Increments per revolution
LED	Light Emitting Diode
MR-brake	Magneto-Rheological brake actuator
PCB	Printed Circuit Board
PWM	Pulse Witdh Modulated
RL	Rear Left Node
RR	Rear Right Node
TDMA	Time Division Multiple Access
TTCAN	Time Triggered CAN
TTP/C	Time Trigged Protocol class C
WCET	Worst Case Execution Time
VDC	Volt Direct Current

Contents

Chapter 1

Introduction

Today, it is getting more and more common to replace, or complement, mechanical solutions with a computer based control system, in order to enhance functionality. Also, some complex machines would not be possible to construct at all, without the aid of this type of systems. The Airbus A340, Boeing 777, and JAS 39 Gripen are just a few examples, which all completely rely on computer based control [40].

Although the vehicle industry has not yet come that far, a new car already has several systems of this kind installed as standard equipment. Research and development in this area is, however, constantly increasing and several companies, including Volvo Cars, have been investigating the possibilities to use this technique to further enhance the car functionality for some time now.

The expressions "Drive-by-Wire" or "X-by-Wire"[1] are often use to describe one type of enhancement considered. These expressions have different meaning depending on the person asked, but usually, they refer to a replacement of a safety critical mechanical solution (the brake system for example) with a computer controlled sensor and actuator system.

1.1 Project Background

During autumn 2000 a final year project for the Master Students in Mechanical Engineering at Luleå university of technology, called "Sirius — Kreativ produktutveckling", was initiated. On commission of Volvo Cars in Göteborg, the students implemented an X-by-Wire system into a car, a Tiger Cat E1 (see Figure1.1), using a new method specially designed to consider reliability during the development process of coupled systems[2]. The project ended late May 2001 and the result was a four wheel steered car where all mechanical connections between driver and the rest of the system were replaced with sensors, actuators and a distributed real-time controller network — see the Luleå Sirius project report [36]. Even though the car at this point was steerable, far from all the functionality the equipment allowed was implemented in software.

[1]The "X" in X-by-Wire could be replaced by "Brake", "Steer" or "'Clutch".

[2]A collection of sub-systems, which depend on each other in order to function.

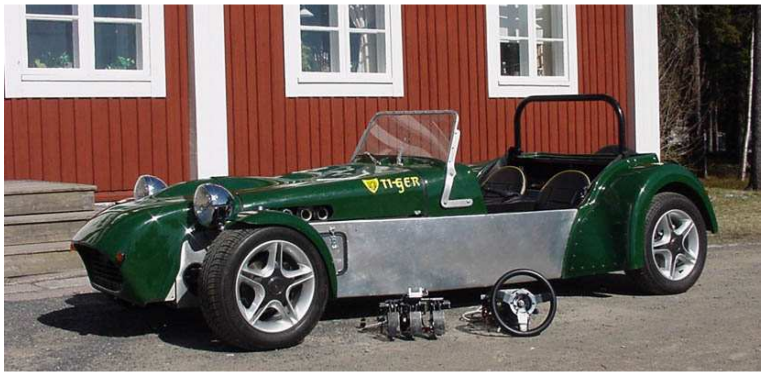

Figure 1.1. The Tiger Cat E1 X-by-Wire prototype car (figure taken from [36]).

The car was soon after moved to Volvo Cars in Göteborg where a couple of additional projects were performed before it arrived to the Department of Mechanical Engineering, Linköpings universitet.

At this point the car was no longer functioning — the rear wheels had been disconnected due do a replacement of sensors which had not been tested, and the front wheels had almost a life of their own when driving the car. Also, the software implementation of algorithms and regulators needed a fair amount of work.

This Master Thesis project was initiated in order to fix these problems, and get the car up an running.

1.2 Purpose

The purpose of this report is not only to describe the work done during this project — it should also serve as a shorthand introduction to the car, in order to lower the threshold for future projects.

As the substance of the report is of a technical character, the intended reader is a person with an engineering background. On the other hand, anyone with an interest in the possible future of the vehicle industry would also benefit from it.

1.2.1 Objective

The main objective of this project is to modify the car so a useable and functional concept prototype is obtained. To achieve this, the following goals have been set;

- The different parts included in the control system should be identified and well documented.
- The implemented controllers and algorithms should be modified so the car behaves in a consistent manner when driven.

- The system should be able to handle redundant components in order to detect faults.

These goals should be implemented in hardware and software in such a way that the car can be used as a platform for laboratory or research projects in the future.

1.2.2 Limitations

As the objective definition is fairly open and the available time limited, a few limitations on the scope of the project are applied .

First, no evaluation of the installed network or the protocol is performed. See [14, 33] where the TTP/C[3] and the CAN[4] protocols are compared, and [22] for a brief introduction to alternatives to TTP/C (TTCAN[5], FlexRay[6] etc.).

As the first of the above goals states, only the parts which build up the X-by-Wire system are covered in detail. All other parts like the engine, power train, ignition system etc. are only mentioned briefly.

The implementation of fault tolerance is also restricted to manage only fault detection — not handle any failure modes. This means that the system should be able to detect if, for example, a sensor is malfunctioning but not react in any special way if, or when, that happens.

1.3 Report Structure

The report is structured as a working procedure for the system at hand. The chapters describe the different steps involved when working with the system, and their order resembles to the order in which the steps should be performed — i.e before a controller structure can be made, demands on system performance are needed, and a schedule cannot be made unless the all task are defined, which in turn require detailed knowledge about the system. This is important to keep in mind, specially for anyone who intends working with the system.

Chapter 2 gives an brief introduction to the car and its history. However, the focus is on the installed parts and their function in the car.

Chapter 3 treats mechanical and electrical modifications that have been performed during the project.

Chapter 4 considers how to make all parts work together as a whole. This involve a discussion on possibilities and drawbacks with a safety critical systems, as well as considerations regarding algorithms and controllers.

[3]Time Triggered Protocol class C
[4]Controller Area Network
[5]Time Triggered CAN
[6]The FlexRay protocol was developed by the FlexRay Group which started as a co-operation between BMW and DaimlerChrysler in 1998.

Chapter 5 treats the actual construction and implementation of the algorithms and controllers used. It describes the step from the overall demands to something that can be used in practice.

Chapter 6 covers the steps to be taken to get the system up and running. This involves defining tasks, messages, and a schedule[7].

Chapter 7 includes results from different tests performed on the system. It gives feedback on how well the practical results relate to the simulated ones.

Chapter 8 summarizes the work done and presents conclusions made. Also, comments on future work are found here.

Appendix A gives an introduction to the software tools used to program the network.

Appendix B presents a detailed diagram of the power distribution to the installed hardware.

Appendix C includes circuit diagrams for all adapting electronics used in the car.

Appendix D gives an detailed explanation on how to connect the wires to the circuit boards used.

Appendix E lists the manufacture drawings made.

[7]This is a description of when the system should do what.

Chapter 2

Inventory

Before any work can be done, detailed knowledge about the car and installed components is needed. In this chapter, the car is first examined at a macro level to give an overall picture. Later, each component in the X-by-Wire system is covered in more detail, starting with the most complex part — the network. Thereafter mechanical components such as sensors and actuators are analyzed, and last but not least the surrounding electronics needed to adapt signals between components and the network are examined. Please note, that the hardware listing only apply to the car's present state during the end of this project.

First, however, a clarification regarding the use of expressions should be noted. In the following sections (and in the rest of the report) the expression "Node" will be used frequently (Node CL for example). It should NOT be confused with "PowerNode", as "Node" refers to a collection of equipment fitted inside a protective housing, or the housing itself. The expression "PowerNode" refers to a special piece of hardware and is part of the equipment inside the housing.

2.1 Car Overview

As mentioned briefly in Chapter 1, the car is a Tiger Cat E1 - a replica of the old Lotus Super 7 racing car, but modified during a final year project by students at Luleå university of technology into a complete X-by-Wire vehicle. In co-operation with Volvo Cars in Göteborg the project design task was to deploy solutions for the steering- and braking systems, in order to allow the car to turn around its own axle, be moved in parallel, and have both the left- and right hand steering. Another design task was to modify the engine suspension in order to reduce vibrations during idle running.

At the end of the project the students had indeed succeeded in their task and were able to demonstrate a functional prototype. To achieve their goals, all mechanical connections between the driver controls (i.e. steering wheel and pedals) and the rest of the car, were removed. Instead, sensors and actuators were installed and connected via a distributed real-time controller network.

To be able to switch between right and left hand steering, the students constructed movable modules of the steering wheel and the pedals, which easily could be fitted to the left or right hand side. The modules are seen lying on the ground in front of the car in Figure 1.1. As the car should be equipped with four wheel steering, the rear suspension was completely modified and parts in the drive chain had to be replaced with a type that would allow the wheel to change the steering angle.

Also, the engine suspension was modified and an actuator was fitted on one of the engine bearers. The actuator created vibrations in opposition on the engine's, and in that reducing the overall vibrations in the car. Although the actuator still is fitted, it was just tested to verify its function and has never been used since.

Before going on specifying the components which constitutes the X-by-Wire system, there are some parts worth mentioning which have not been modified compared to the original car. Originally, the Tiger Cat E1 is composed of parts from other car models, normally a Ford Sierra. This car is no exception. Under the glass fibre cap, a 2.0 litre, 4 cylinder Ford engine is found, giving about 140 hp[1] (in this light car that gives enough power to do 0 - 100 km/h in less then 5 seconds). Among other parts the Sierra has contributed with, are the two DELLORTO DHLA 40 H carburettors, the 5-speed gearbox, and the ignition system.

2.2 Network and Connections

The real-time controller network plays a central role in an X-by-Wire system and it has essentially three important tasks to perform;

Information exchange. When turning the steering wheel you would also expect the wheels to turn. The network has to provide the connection between these parts so they can communicate with each other.

Sensor data collection. When pressing the brake pedal, a sensor registers a change in the pedal angle. The network then has to collect the sensor data and translate it into a reference value for the brake pressure, for example.

Actuator control. Assume that a throttle valve reference value has been set, and it has been correctly transmitted to the part where the throttle valve actuator is connected. The network then has to make sure that the actuator is in fact following that reference.

Some of the examples described above are critical for the function of the car, and it is of great importance that the controller network can perform the tasks with a high degree of safety and reliability.

For a long time now the car industry has been (and still is) using the CAN protocol to communicate between different systems in a car, and is is sufficient for the applications used today. However, it lacks many requirements, especially regarding safety, needed in a distributed safety-critical real-time system like this (i.e.

[1]horse power

steer- and brake-by-wire applications). To meet these requirements the TTP/C protocol was developed some ten years ago by the Vienna University of Technology and Daimler-Benz Research. Later, in 1998, an Austrian company, TTTech, was formed to develop tools and hardware using the TTP concept. For a more comprehensive introduction to the history of the TTP/C protocol, please refer to [22].

The base of this concept is the TTTech C1 PowerNode [41] (see Figure 2.1), which is equipped with TTTech's own TTP/C-C1 network controller chip for information exchange, and a Motorola embedded Power PC processor[2] for sensor data collection and actuator control.

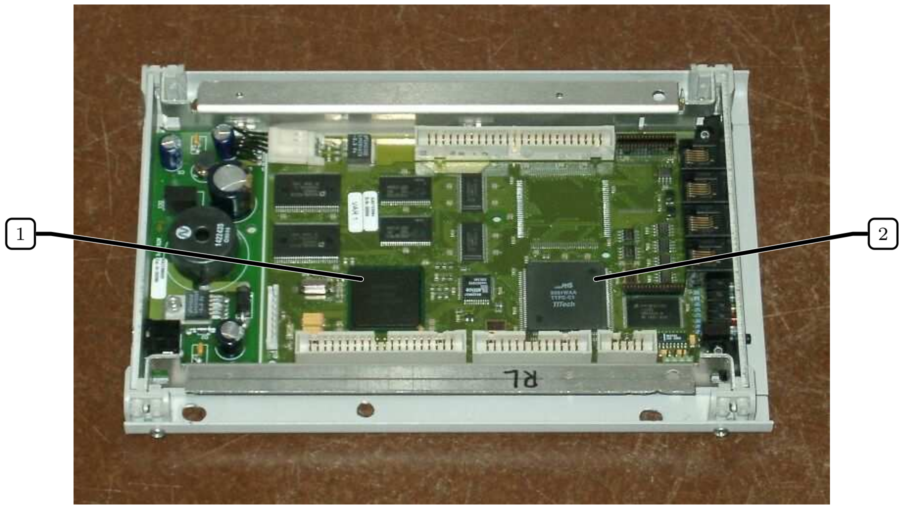

Figure 2.1. The TTTech C1 PowerNode which form the base of the network. The two large circuits on the board are the Power PC processor (no. 1) and the TTP/C-C1 network controller (no. 2).

A network, or a cluster, is composed of two or more PowerNodes, which are connected to each other via a broadcast data bus[3] using either a "bus" or a "star" network topology [42], and communicate using the TTP/C protocol. The network in this car consists of six PowerNodes located at strategic places (see below for detailed locations), which are connected to each other using the bus topology[4]. The installed sensors and actuators are in turn connected to these PowerNodes — see Figure 2.2 where each PowerNode is listed with its surrounding components.

[2](MPC555 Black Oak, [30])

[3]All nodes participating in the cluster receives every message sent on the network.

[4]Although the star topology introduces a higher degree of safety in the system, it has not been used since the old version of the software tools used at Luleå did not support it.

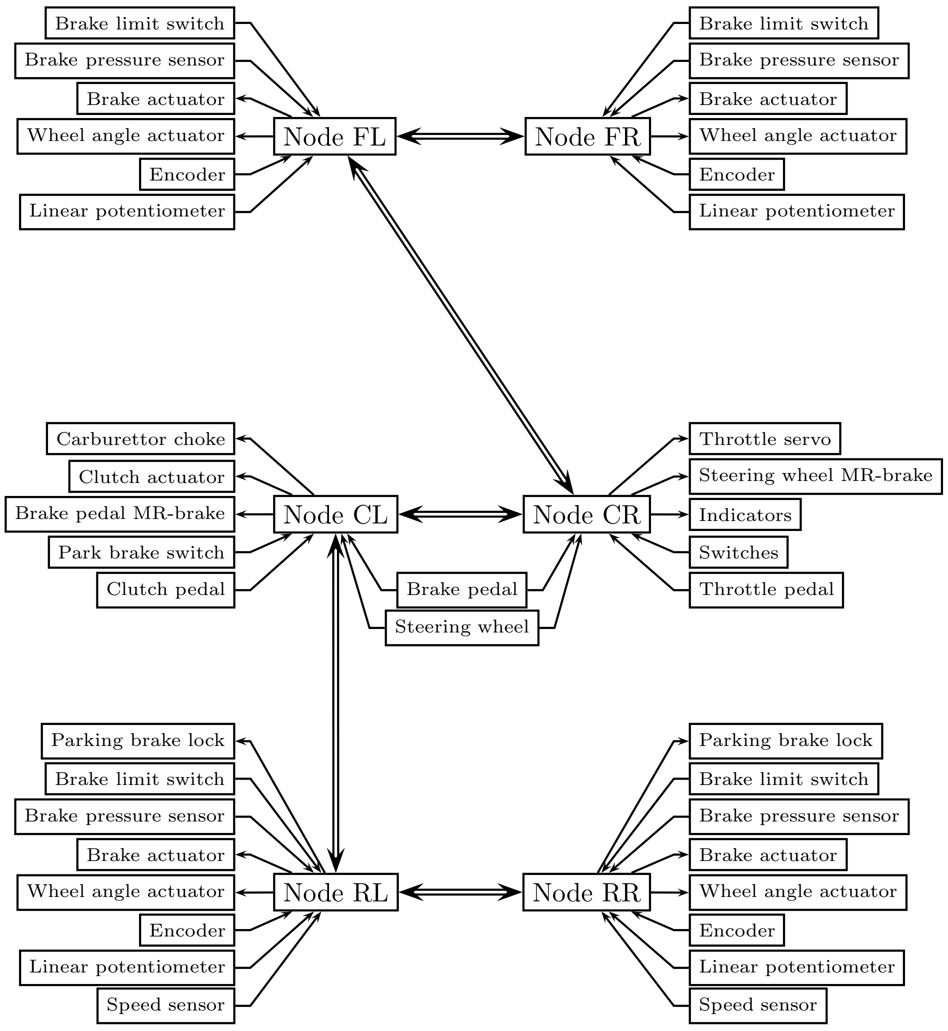

Figure 2.2. An overview of the network and how the different components are connected to each other. CL - Central Left, CR - Central Right, FL - Front Left, FR - Front Right RL - Rear Left, RR - Rear Right.

2.2.1 Node CL

Node CL[5] is found on the left side, just in front of the dash board (the grey box to the left in Figure 2.3), where it controls the clutch actuator and the brake pedal MR-brake[6]. The MR-brake is, however, not actually plugged into the node, but the wires are prepared for prospective connection. Other equipment connected to the node are the clutch pedal sensor, the parking brake switch (the upper left switch in Figure 2.4), one brake pedal sensor and one of the steering wheel encoders.

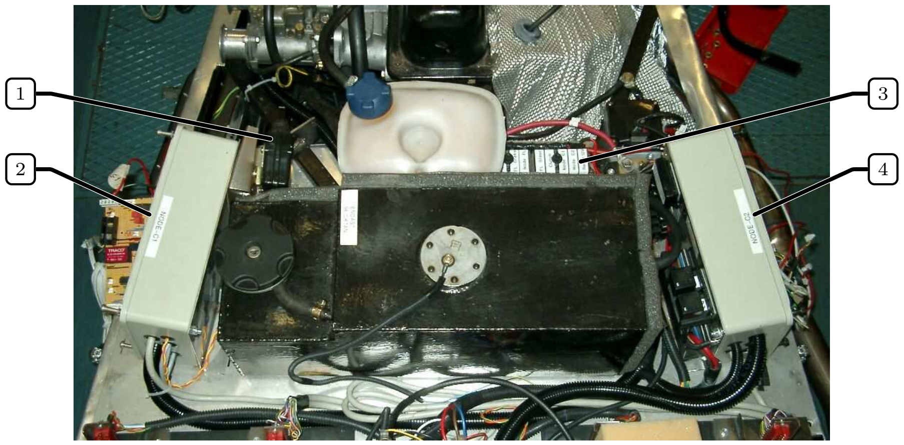

Figure 2.3. The centre nodes are located on each side of the black fuel tank in the middle of the figure — Node CL (no. 2) to the left and Node CR (no. 4) to the right. Also seen in the figure are the carburettor choke (no. 1) (i.e. the cold start enrichment device) and the fuse box (no. 3), which contain power supply fuses for the centre nodes, the front nodes, as well as for the actuators connected to these.

2.2.2 Node CR

Node CR[7] is located opposite to Node CL (the box to the right in Figure 2.3) and controls the steering wheel MR-brake, the throttle servo and the four LED:s[8] in the middle of the dash board (see Figure 2.4). The other brake pedal sensor, the throttle pedal sensor, the second steering wheel encoder, and the rest of the dash board switches (all except the parking brake switch) are also connected to this node. Please note that all switches are two-way (i.e. ON/OFF), except for one, which is three-way.

[5]Central Left
[6]Magneto-Rheological brake
[7]Central Right
[8]Light Emitting Diode

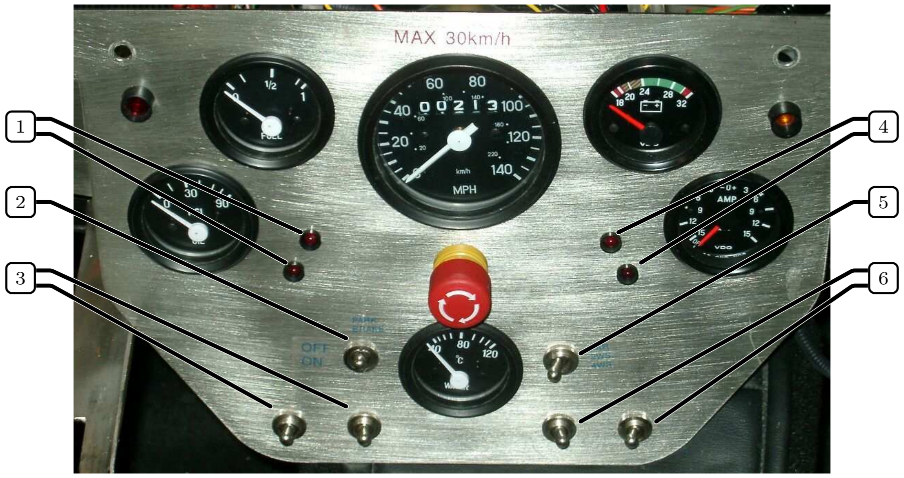

Figure 2.4. The dash board with switches. The upper left one is the parking brake switch (no. 2) and is connected to Node CL. The rest of the two-way switches (no. 3, 6), as well as the single three-way switch (no. 5), are connected to Node CR, and their function is controlled by the software implementation in the PowerNode. The same is true for the four LED:s (no. 1, 4), located just below the gauge indicators.

2.2.3 Wheel Nodes

The four wheel nodes (Node RL, RR, FL, and FR[9]) all have similar tasks, i.e. controlling braking and steering for one wheel each. The two front nodes are located on either side of the radiator (see Figure 2.5) and the rear nodes are located just behind the seats (see Figure 2.6). They are connected to the wheel actuators, the wheel angle encoders, the wheel actuator potentiometer, the brake actuators, and the brake pressure sensor. In addition to this, the two rear nodes have a special brake directly attached on the motor axle on the brake actuators (see below for details) and a speed sensor connected to them.

[9]Rear Left, Rear Right, Front Left and Front Right

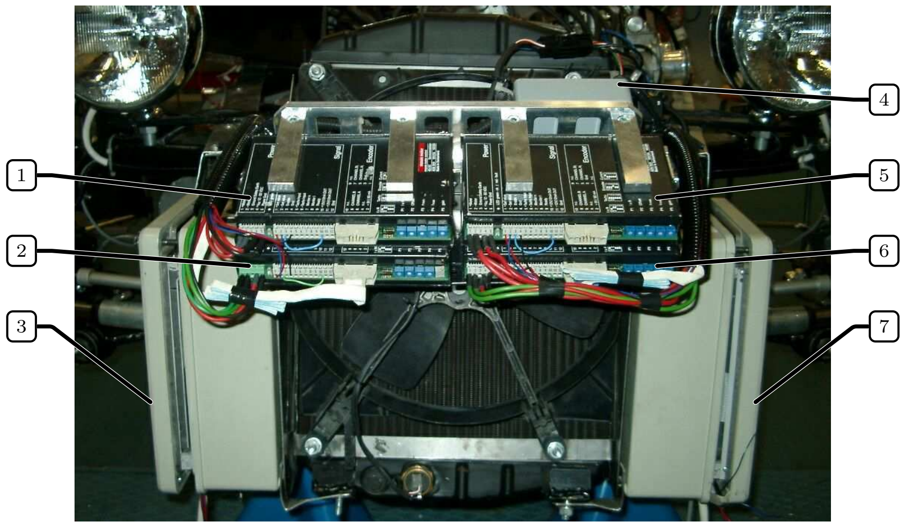

Figure 2.5. Node FL (no. 7) and Node FR (no. 3) are located on each side of the core fan, and the motor control boxes for the front wheel actuators are placed just in front of it. The two upper boxes (no. 1, 5) control the brake actuators and the two lower ones (no. 2, 6) the steer actuators. Also, in the top of the figure, the steer actuator choke box (no. 4) is seen.

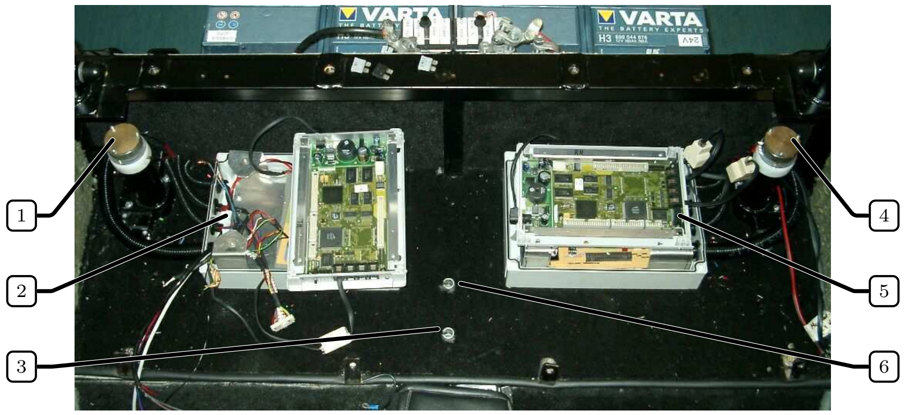

Figure 2.6. The rear nodes are placed just behind the seats – Node RL (no. 5) behind left seat and Node RR (no. 2) behind the right. The rear brake actuators are also located here, outside each node (no. 1, 4). The two small holes in the middle are the battery master switches for the 12 V (no. 3) and 24 V (no. 6) systems respectively.

2.3 Mechanical Components

The car is equipped with a number of sensors and actuators to be able to control the system. In the following sections the different components are listed together with a short description of where they are mounted in the car and what function they have in the system. Also, some important technical specifications are listed in tables.

2.3.1 Actuators

There are three different types of actuators performing different types of tasks - linear ball screw actuators for linear motion, servos for rotational motion and MR-brakes for force feedback.

To change the steering angle, four identical ball screw actuators[10] are mounted at each wheel, connecting the steering spindle to the frame. The motions of the actuators are made possible by DC[11] motors[12] with an encoder[13] mounted on the outer end of the motor axle (see Figure 2.7).

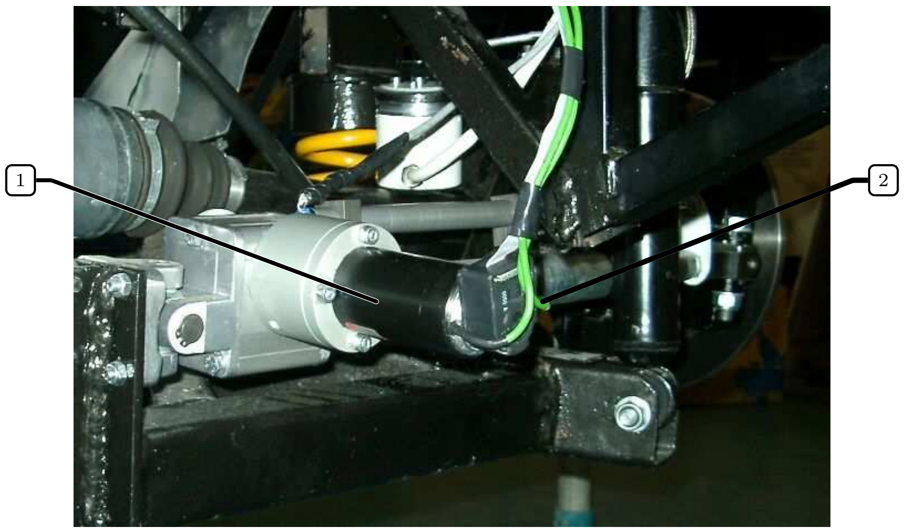

Figure 2.7. The rear right steer actuator DC motor (no. 1). The encoder (no. 2) is seen mounted on the outer end of the motor axle.

The motor and encoder are connected to a special motor control box, specified later in this chapter. To protect the box from the heavy current draw when

[10]SKF CARN 32x200x4, [38]
[11]Direct Current
[12]maxon RE 40 148867, [25]
[13]maxon HEDL-5540 110513, [29]

starting the motor, a choke[14] have been inserted between the power cables (a choke consist of two iron-cored coils connected in parallel, and are used to increase a DC motor's terminal inductance). The chokes are fitted in the car between the rear motor control boxes (as shown in Figure 2.8) and on top of the front control box mounting (the small gray box seen to the upper right in Figure 2.5).

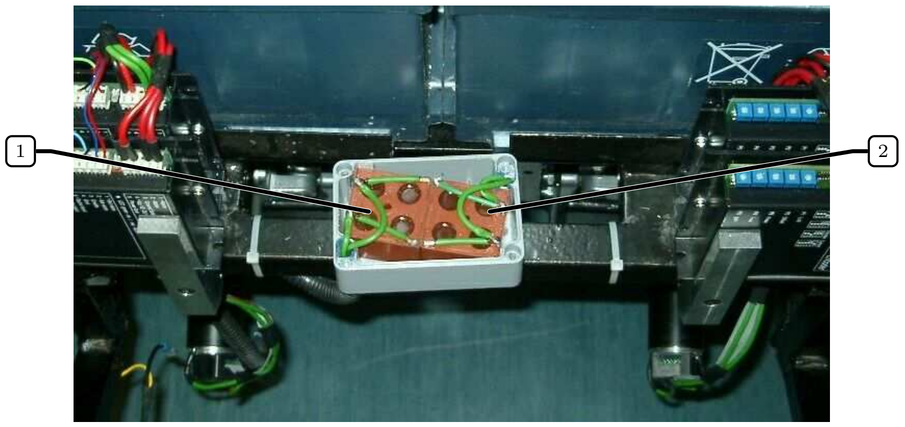

Figure 2.8. The rear chokes inside its protective housing. The left choke (no. 1) is connected to the left steer actuator DC motor, and the right (no. 2) to the right motor. The chokes prevent the DC motors from damaging the control boxes, by increasing the motors terminal inductance.

As this car is a complete X-by-Wire vehicle, the clutch wire has been disconnected from the pedals and instead a ball screw actuator[15] has been installed to pull the wire. It is mounted just above the gearbox behind the engine — in the centre of Figure 2.9 the circular shaped DC motor of the actuator is shown and Figure 2.10 shows the actuator mounting above the gearbox. This actuator has a sensor fitted inside, which measures the actuator length by detecting the position directly on the moving nut. The DC motor is mounted on top of the actuator, and together with the sensor it is connected to the clutch actuator control box.

Some specifications regarding the ball screw actuators mentioned above are listed in Table 2.1.

[14]maxon 133350, [28]
[15]SKF CAPR 43Ax100x2A1G3F / D24C, [37]

Table 2.1. Specifications for the ball screw actuators.

Property	**CARN 32**	**CAPR 43A**
Function	Steering	Clutch
Stroke	200 mm	100 mm
Gear ratio	1:6.25	1:12.5
Output speed range	0 - 75 mm/s	0 - 26 mm/s
Motor	maxon RE 40	SKF D24C flat motor

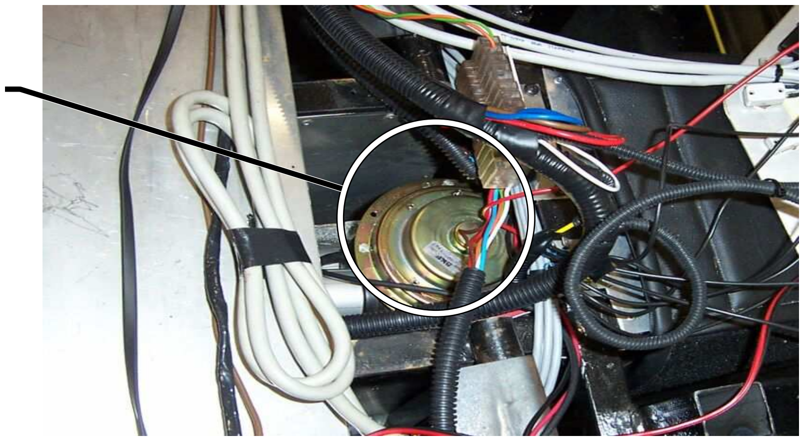

Figure 2.9. The clutch actuator seen from above. The circular shaped DC motor is seen in the middle of the figure.

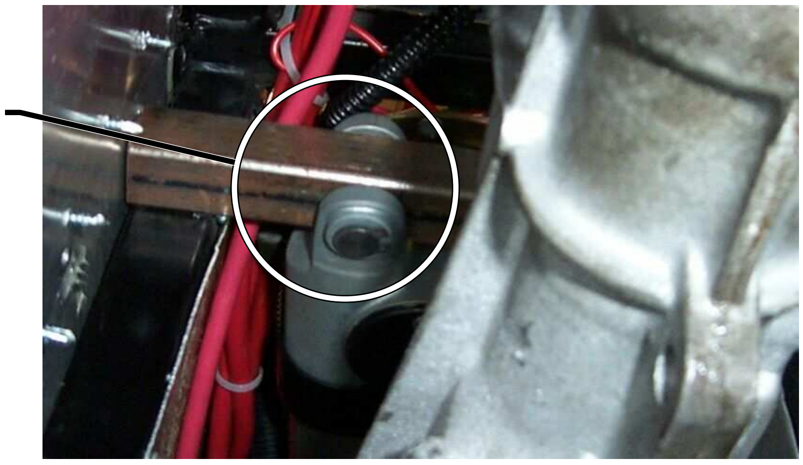

Figure 2.10. The clutch actuator viewed from underneath the car. Behind the aluminium gearbox, the mounting of the actuator is seen.

Except for the DC motors mentioned above, another type is used in the braking system. Here, the conventional master cylinder (normally mounted just in front of the braking pedal, on the separation wall between the engine and the driver compartments) has been replaced. Instead, a system made up of four independent hydraulic pumps has been designed [35], and fitted close to each wheel. The front wheel pumps have been mounted inside each steering spindle (see Figure 2.11) and the rear ones behind the seats, next to the rear nodes (see Figure 2.3).

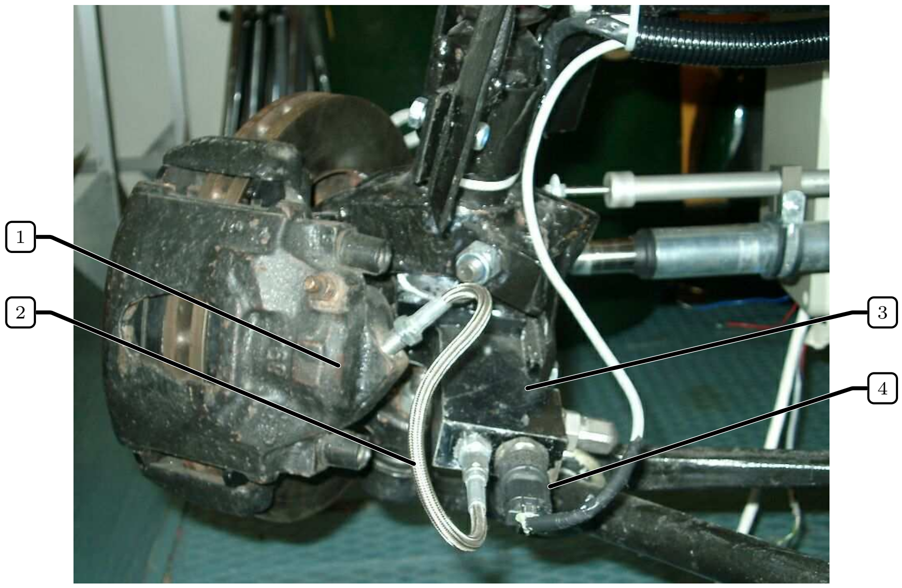

Figure 2.11. The front left steer spindle - notice the brake actuator pump (no. 3) in the middle of the figure, fitted inside the spindle. Other parts seen in the figure are the brake caliper (no. 1), the armoured hose (no. 2) and the brake pressure sensor (no. 4).

The actuator consist of a DC motor[16] and a gearbox[17] mounted on a steel block, functioning as a cylinder. The motor operates on a piston inside the cylinder, via the gearbox and a gear wheel. The original brake caliper[18] has been connected to the other end of the cylinder, via an armored hose.

To compensate for the increased oil volume, due to brake pad ware, a small hydraulic tank with a non return valve have been fitted on the side of the steel block. The valve prevents the oil from going backwards through the tank when the piston is pushed forward, i.e. when the pressure in the system is increasing. Two sensors have also been installed on the block — a pressure sensor has been mounted just beside the hose, and a limit switch is found at the other end the

[16]maxon RE 35 118777, [24]
[17]maxon GP 32A 110367, [23]
[18]Swedish: bromsok

block. In Figure 2.12 all the different parts of the brake actuator have been laid out - note the limit switch cables running out of the cylinder block.

In addition to the parts mentioned above, the rear DC motors have a special brake[19] directly attached on the motor axle. These brakes function as a park brake by locking the axle when the power is turned off. Of course, the pressure must first be increased in the system before the axle is locked, but that is handled by the control system. The motor power cables are in turn connected to a motor control box (specified later in this chapter), similar to the ones used for the wheel actuator motors.

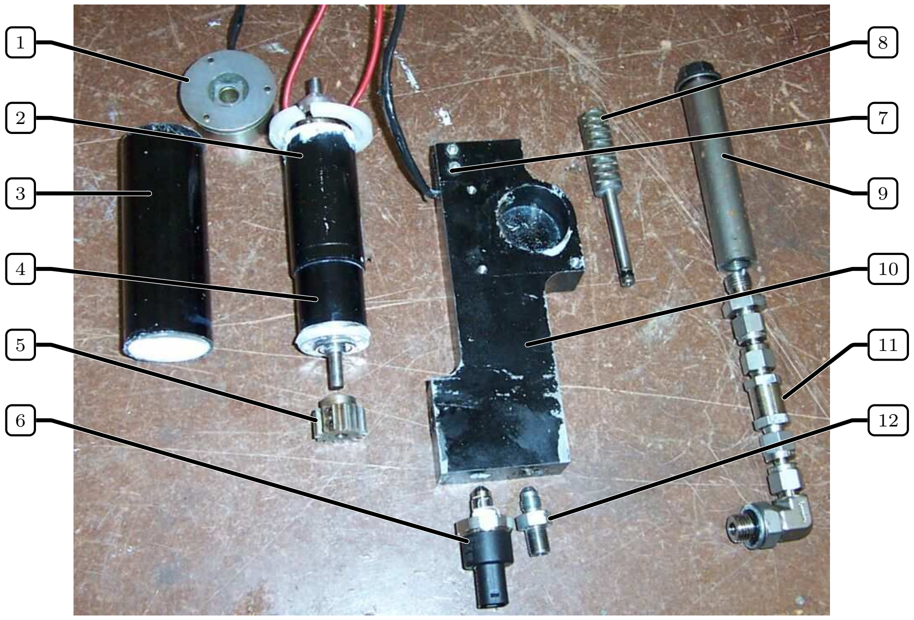

Figure 2.12. The different parts of the (rear left) brake actuator pump. Starting from the left, the protective housing (no. 3) for the DC motor and the gear box is seen, followed by the parking brake lock mechanism (no. 1). Thereafter comes the DC motor (no. 2) and gear box (no. 4) with the gear wheel (no. 5) just below. Then there is the cylinder block (no. 10) with the limit switch (no. 7) in the top end and the pressure sensor (no. 6) (together with a nipple (no. 12) for connecting the hose) in the other. The last three parts are the piston (no. 8), the hydraulic tank (no. 9) and the non return valve (no. 11).

In Table 2.2 specifications regarding DC motors and used gearboxes (when appropriate) are found.

[19]Östergrens Elmotor AB FSB003, [32]

Table 2.2. Specifications regarding the DC motors and gear boxes.

Property	**maxon RE 40**	**maxon RE 35**	**SKF D24C**
Function	Steering	Braking system	Clutch
Power rating	150 W	90 W	n/a
Nominal voltage	24 VDC	30 VDC	24 VDC
Gear box, ratio	n/a	maxon GP 32A, 23:1	n/a
No load speed	7580 rpm	7220 rpm	n/a
Max. continuous current	6 A	2.74 A	9 A
Motor control box	maxon ADS 50/10 201583	maxon ADS 50/5 145391	SKF CAED 9-24R-PO

To be able to change the throttle valve opening in the carburettors, a servo[20] has been mounted underneath the intake manifold. Due to the lack of space, the servo is not directly attached to the throttle valve — instead a flexible steel wire has been installed between the servo output wheel and the valve arm (the wheel is seen in Figure 2.13).

The carburettors also have a cold start enrichment device, commonly known as a “carburettor choke” (not to be confused with DC motor chokes mentioned earlier), which is controlled by a car door lock servo[21] mounted behind Node CL (see Figure 2.3).

[20] HiTEC HS-805BB+, [11, 12]
[21] VDO IMP 6880, no specification available

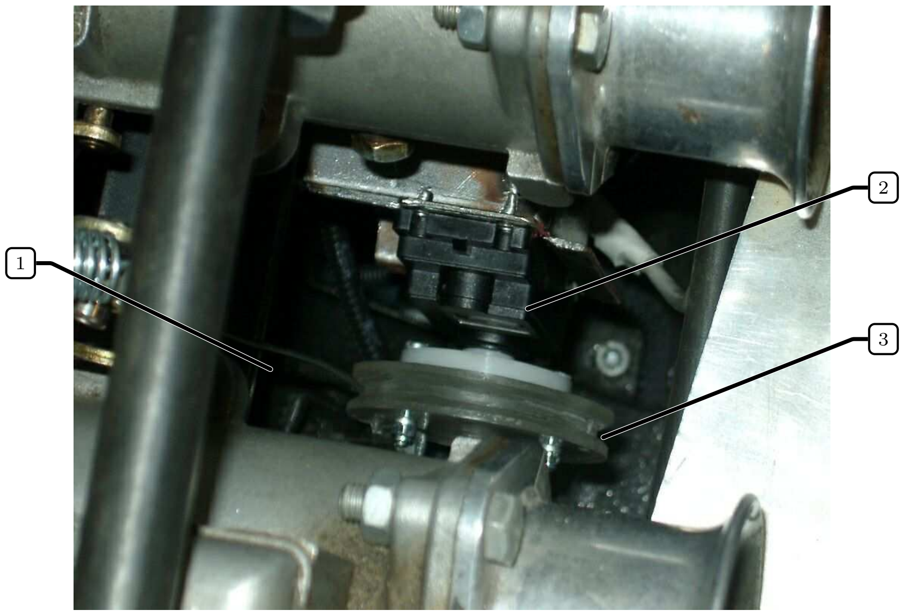

Figure 2.13. The throttle servo (no. 2) viewed from above the carburettors. Just below the centre of the figure, the wheel (no. 3) attached to the servo output is seen. Slightly to the left of that, connected to the wheel, is the flexible steel wire (no. 1) going up to the throttle valve.

Last but not least, there are two MR-brakes installed in the car. They are both used to apply some sense of force feedback to the driver by increasing the friction. The first one[22] has been attached directly on main shaft in the movable steering module (see Figure 2.14). The second one[23] has been installed in the pedal module (see Figure 2.15) acting on the brake pedal.

The MR-brake in the steering module is controlled by a special control card[24] located inside Node CR (the card is seen in Figure 2.21). The other MR-brake, however, also needs a controller card similar to the other, but although preparations have been made to add one, the actual card is yet to be found.

[22] LORD RD-2028-18X-ol, [19]
[23] LORD MRB-2107-3, [18, 20]
[24] LORD RD-3002-03, [21]

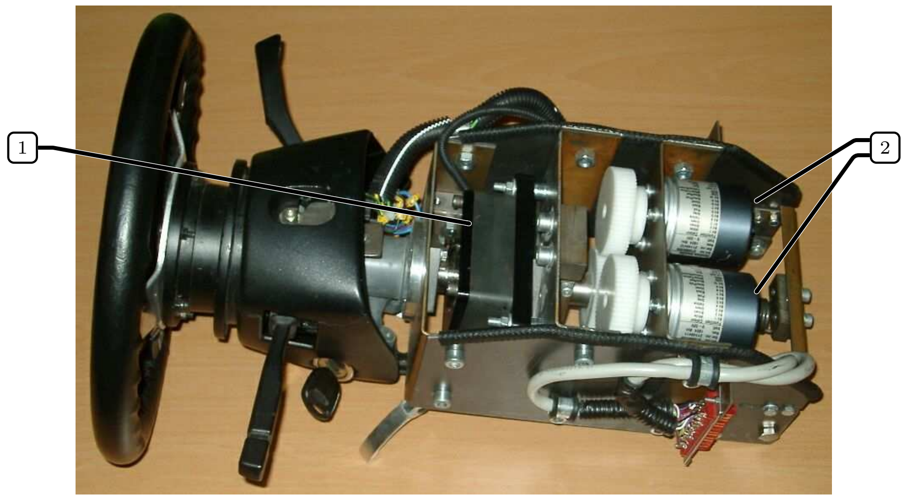

Figure 2.14. The movable steer module. The steering wheel MR-brake (no. 1) is seen in the middle of the module, and the two absolute encoders (no. 2) are found further to the right in the figure.

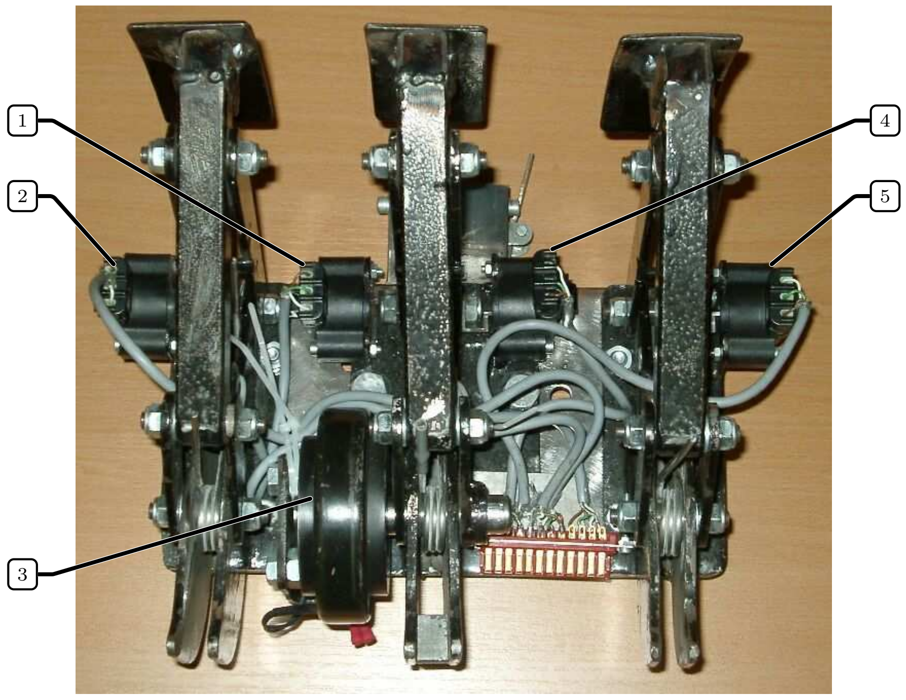

Figure 2.15. The pedal module. Note the duplicated sensors (no. 1, 4) and the MR-brake (no. 3) attached on the brake (middle) pedal. The clutch pedal sensor (no. 2) and the sensor for the accelerator pedal (no. 5), are seen at the outer ends of the figure.

2.3.2 Sensors

The car is equipped with both digital and analog sensors. At each wheel, a 14 bit digital absolute shaft encoder[25] has been installed to measure the wheel angle. The encoders at the front have been mounted on top of the upper lever arm[26] and measure the angle of the spindle (see Figure 2.16).

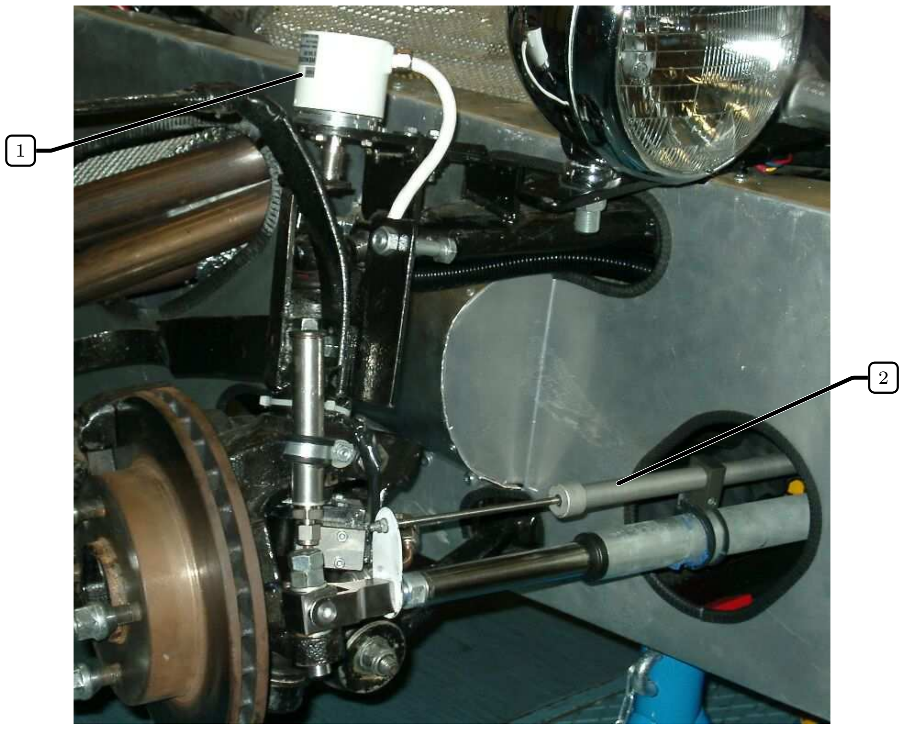

Figure 2.16. The front right wheel angle sensors. The absolute shaft encoder (no. 1) is seen mounted on the upper lever arm, and towards the bottom right corner in the figure, fitted on top of the ball screw actuator, is the linear position sensor (no. 2).

In contrast to the front wheel, the rear wheel encoders have not been directly attached to the spindles due to lack of space. Instead, they have been moved towards the centre of the car and measure the wheel angle via a linkage (see Figure 2.17).

[25]Hengstler RA58-S, [8, 9]
[26]Swedish: länkarm

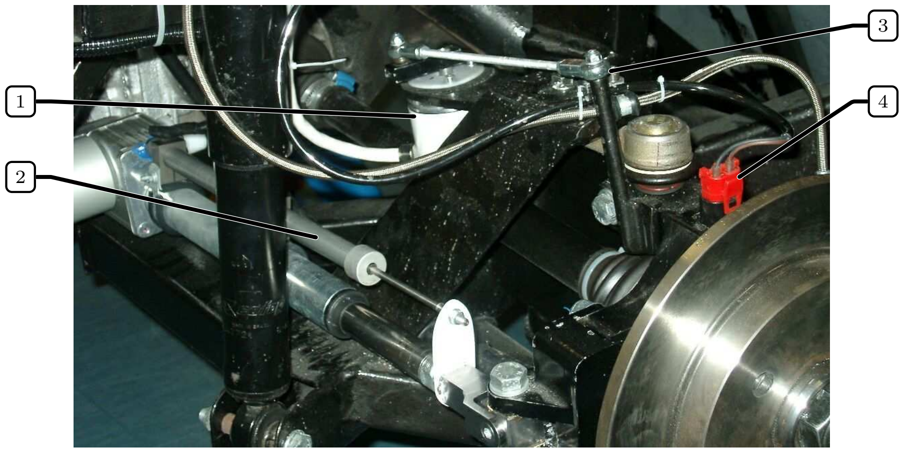

Figure 2.17. The figure shows the rear right encoder (no. 1) with linkage (no. 3) to the spindle, the linear position sensor (no. 2) on top of the ball screw actuator, and the speed sensor (no. 4) fitted inside the spindle (partly concealed by the brake disc).

Another type of encoder[27] with a resolution of 10 bit, is found mounted in the moveable steering module (see Figure 2.14). Here, two identical encoders have been mounted next to each other to measure the steering wheel angle. The encoders are in turn connected to different nodes — one to Node CL and one to Node CR.

In Table 2.3 some additional specifications regarding the absolute shaft encoders are found.

Table 2.3. Specifications for absolute shaft encoders

Property	**Leine & Linde 670**	**Hengstler RA58-S**
Measures	Steering wheel angle	Wheel angle
Resolution	10 bit (1024 inc/rev)	14 bit (16384 inc/rev)
Code switching frequency	max 50 kHz	max 100 kHz
Supply voltage	9 - 30 VDC	5 VDC
Max current consumption	70 mA @ 24 VDC	600 mA

As mentioned earlier the system is equipped with several analog sensors. On top of the four wheel actuators, linear position sensors[28] have been mounted (see

[27]Leine & Linde 670 670066350, [17, 16]
[28]BEIDuncan 610, [1]

Figure 2.16 and 2.17). In principle, these sensors are doing the same job as the digital encoders mounted on the steering spindle, i.e. they measure the wheel angle.

In the movable pedal module, four identical analog angular sensors[29] are fitted, which measures the angular displacement of the shafts when any of the pedals are pressed (see Figure 2.15). The accelerator pedal and the clutch pedal have one sensor each, and the braking pedal is equipped with two sensors.

The four independent brake actuators are equipped with one pressure sensor[30] and one micro switch[31] each. Both are mounted on the cylinder block (the pressure sensor is seen at the bottom in Figure 2.12). The pressure sensor is of course used for measuring the oil pressure in the system and the micro switch is used to indicate when the piston is in its rear end position.

Finally, the car is equipped with two inductive speed sensors[32] mounted inside the rear steering spindles (see Figure 2.17). These sensors are used to measure the wheel angular velocity, i.e. the speed of the vehicle, since the normal speedometer is a pure mechanical construction. The sensors register the change in the magnetic field when a tooth gap in the gear wheel, fitted on the axle shaft, passes by.

2.4 Power and Electronics

Not only does all equipment need some kind of power source in order to function, the PowerNodes also need a number of surrounding electronic components to help them interact with the rest of the parts in the system. These components are classified into two categories — motor control boxes which amplify control signals to the actuator motors, and electronics to adapt and filter signals coming in to and going out of the nodes.

2.4.1 Electric Power Supply

As in all systems which include any type of electrical devices, a power supply is needed. This car has two separate supply systems — one 24 V system and one 12 V system. The 12 V system is used for all the standard equipment in the car, among these are the ignition system, head lights etc. It will not be described in further detail in this report, since it does not interact with the "by-Wire" part of the car. The 24 V system, on the other hand, is indeed interesting, since it supplies power to all the added X-by-Wire equipment, i.e. network, nodes, actuator control boxes, and sensors.

The base of the 24 V system consists of two 12 V 100 Ah VARTA batteries connected in series. These are located at the back of the car (see Figure 2.18), and are charged with a 24 V 70 A Motorola generator mounted on the right side of the engine. One should note that, although the 12 V system is separated from the 24 V system, it is still connected to one of the batteries, making the load on the two

[29]BEIDuncan MOD.9811, [2]
[30]Bosch 0 265 005303, [3]
[31]Saia-Burgess V4NCSK2, [34]
[32]VOLVO 6849311 0988 10.0711-1146.1, no specification available

batteries differ and the charging difficult. Because of this the batteries should be shifted from time to time.

To protect the equipment, fuses have been put in between each of the connected component and the power supply, i.e. each node and actuator control box has its own fuse. These fuses are found inside two fuse boxes, located on just behind the engine (see Figure 2.3) and above the batteries (see Figure 2.18).

There are also two battery master switches, one for each system, located between Node RL and Node RR just behind the seats in the car (the 24 V master switch is the one closest to the nodes in Figure 2.3).

In Appendix B a schematic overview over the power distribution can be found.

2.4.2 Motor Control

There are three different types of motor control boxes in the car – one type for the steering actuators, one for the brake actuators, and one for the clutch actuator. The boxes make it easy to control the motors and remove the need for analyzing the specific properties of the motor since the boxes are specially constructed for the motor they are connected to.

There are a total of four steering actuator motor control boxes[33] where two are mounted in front of the radiator (the two lower ones in Figure 2.5) and control the front wheel actuators. The other two are mounted behind the batteries (the two closest to the batteries in Figure 2.18) and, of course, control the rear wheel actuators. As seen in Figure 2.5, as well as in Figure 2.18, there are another four motor control boxes[34] not accounted for yet. These control the brake actuator motors.

All of these eight control boxes can be configured to operate in different modes, which specifies how the box should interpret the input, or command, signal. The steer actuator control boxes have been set to "encoder" mode (refer to [27] for details on how to configure the control box), since that will make the control box interpret the input signal as a speed reference. The box will then automatically adjust the output power so the angular velocity of the motor matches the specified input voltage.

The brake actuator control boxes have, on the other hand, been set to "current" mode (refer to [26] for details). The control boxes will in this mode interpret the input signal as a current reference, and adjust the output current so the torque on the motor axle matches the input voltage.

The clutch actuator control box[35] is fitted inside Node CL (the black box in Figure 2.19) and differs from the other control boxes as it is pre-configured to function together with the actuator as a position servo, i.e. the input voltage corresponds to a length on the actuator.

[33]maxon ADS 50/10 201583, [27]
[34]maxon ADS 50/5 145391, [26]
[35]SKF CAED 9-24R-PO, [39]

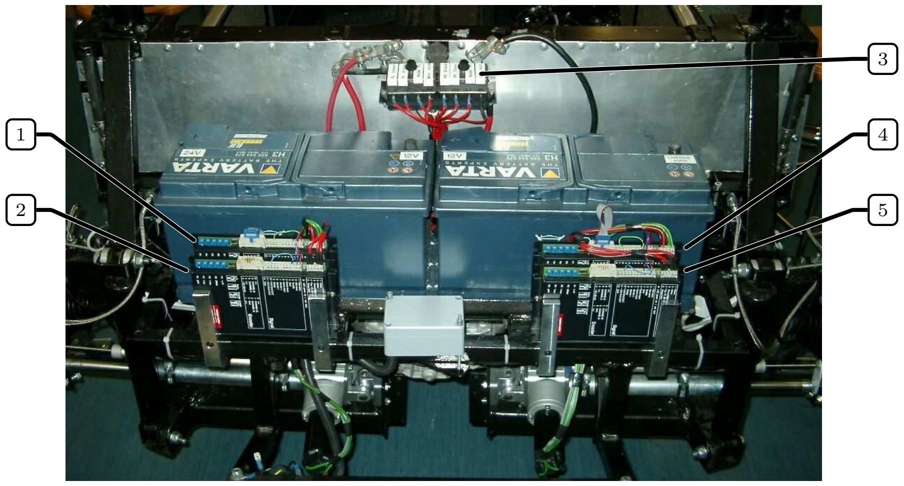

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Figure 2.18. The actuator control boxes for the rear wheel actuators are located just behind the batteries. The two boxes (no. 1, 4) closest to the batteries control the steering wheel actuators and the other two (no. 2, 5) the brake actuators. Also seen at the top of the figure, is the fuse box (no. 3), containing power supply fuses for the rear nodes and actuators.

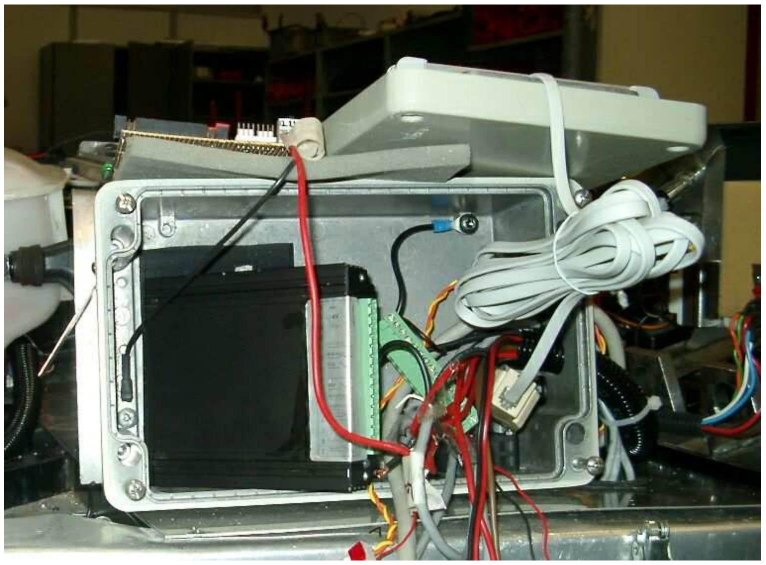


Figure 2.19. The clutch actuator control box located inside Node CL.

2.4.3 Signal Adapting Electronics

Although the PowerNode is very advanced, there are some limitations to what it can do. The maximum voltage allowed on the input pins (both on the digital I/O pins and the analog ports) are 5 V and the output PWM[36]channels can provide signals between 0 and 5 V [41]. To handle these limitations adapting electronics have to be used between the PowerNode and its surrounding equipment. The electronics contribute with essentially three functions;

- Supply the sensors with power.
- Adapt and filter sensor signals to the PowerNode's I/O ports.
- Amplify and filter control signals coming out from the PowerNode.

As the connected equipment differs between the PowerNodes, three different types of circuit boards are found in the car — one type for the wheel nodes and one type each for Node CL and CR. Although there are some differences between the four wheel nodes (Node FL and FR lack speed sensors, and the parking brake lock is only implemented in Node RL and RR) they still have the same type of circuit board.

All circuit boards are supplied by the 24 V system, and the PowerNodes are in turn supplied by the cards. However, in the two centre nodes (Node CL and CR) a 12 V power cord is added to supply the MR-brake controller cards, the steering wheel encoders, and the carburettor choke servo.

Another common factor between the different boards is the analog filters used. They all are first order low-pass filters[37] with a cut-off frequency at 16 Hz.

Two different types of operational amplifiers are also used on the boards. Although they differ in the allowed temperature range and surrounding components, their task (with one exception, see below) is the same — to amplify a signal by a factor of about 2 . To supply power to these amplifiers all boards have a 12 V voltage regulator[38] and a DC/DC converter[39] fitted.

The circuit diagrams of the installed board types are found in Appendix C, and in Appendix D a detailed description on how to connect the different wires to the circuit board is found.

[36]Pulse Width Modulate. A square wave signal where the average voltage is controlled by changing the width of the pulse.

[37]The filter is composed of one 2.2 μF capacitor and a 4.7 kΩ resistor.

[38]The voltage regulator stabilizes an input between 15 to 35 V into a constant output of 12 V.

[39]One input signal of + 12 V is converted into two output signals, one +12 V and one -12 V.

The circuit board for *Node CL* is fitted inside the node housing and is seen in Figure 2.20. The connected digital steering wheel encoder has an output signal voltage of 10 V, which has to be reduced to 5 V before going into the PowerNode's I/O pins. This is done by letting the 10 bit signal pass through a resistor bridge and an electronic protection circuit.

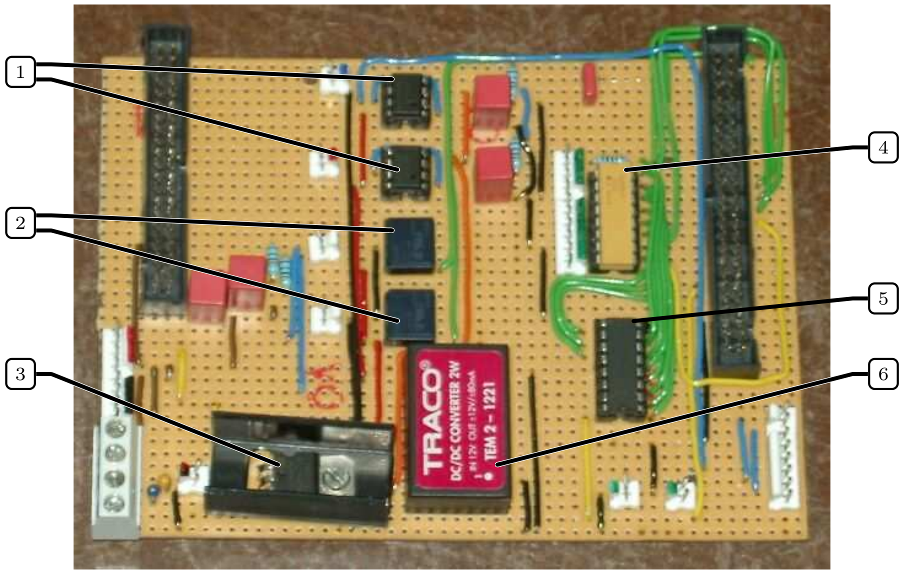


Figure 2.20. The circuit board with adaptive electronics for Node CL. Starting from the upper left corner, the following components are pointed out; operational amplifiers (no. 1), relays (no. 2), 12 V voltage regulator (no. 3), resistor bridge (no. 4) and protection circuit (no. 5) for the encoder signal, DC/DC converter (no. 6).

To reduce high frequency ripple from the analog brake pedal sensor the signal passes through a low-pass filter — the same is true for the clutch pedal sensor. These two sensor signals are connected to the analog ports on the PowerNode.

The only actuators actually connected to this node[40] is the clutch actuator, via its own control box, and the carburettor choke. The required input to the box is a smooth signal between 0 and 10 V, but due to the limitations in the PWM-channels on the PowerNode, the control signal has to be amplified by a factor of 2. Also, since the PWM output is a square wave signal (i.e. contains a lot of high frequency components), it has to be smoothed out. The control signal is therefore passed through a filter and an amplifier stage.

[40]As mentioned earlier, the brake pedal MR-brake is not connected due to the absence of a controller card. However, a filter and an amplifier stage can be found on the card to adapt a future control signal.

The carburettor choke servo is controlled by two relays — one for each direction. The relays are supplied by the 12 V power cord and are directly connected to one PWM-channel each. When the relay is switched on by the PWM signal, the 12 V input is transferred to the output, where the servo is connected.

Last but not least, there is the parking brake switch. Here, no adaptive electronics is needed, i.e. the switch signal is directly passed through to the PowerNode without any components in between. Do note though, that the switch signal is not connected to one of the I/O pins (as would be expected), but to one of the PWM-channels. Although the reason for this has not been explained (please refer to [36, 35]), it is possible to do so, since the PowerNode can be programmed to re-configure a PWM-channel into an I/O pin if needed.

Node CR has a circuit board (see Figure 2.21) quite similar to the one just described. Similar components are used to adapt the second encoder signal, the second brake pedal sensor and the throttle pedal sensor. This is also partly true for the rest of the switches connected to this node, i.e. the signals are passed through with no adaptive components in between. The difference is in the way the switches have been connected to the PowerNode. Instead of using the I/O pins or the PWM-channels (as been done in Node CL), the analog ports have been used. Again, this is not as expected, but possible, way for connecting the switches, since also the analog ports can be re-configured to function as I/O pins.

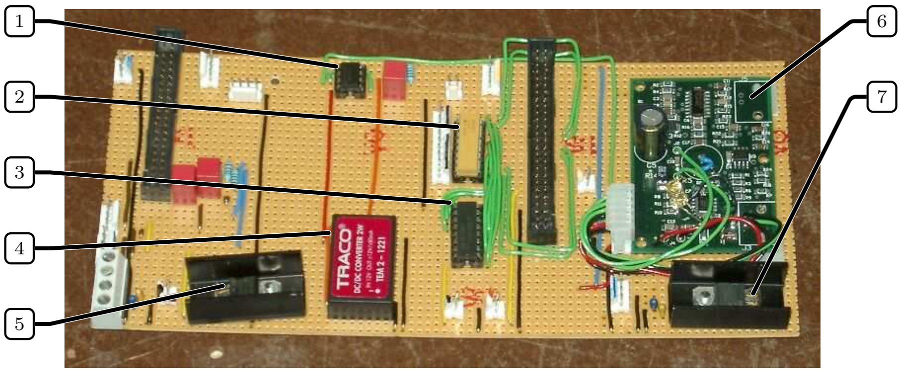


Figure 2.21. The circuit board with adaptive electronics for Node CR. Note the special control card for the steering wheel MR-brake actuator to the right (no. 6). Other components shown are the operational amplifier (no. 1), the resistor bridge (no. 2) and protection circuit (no. 3) for the encoder signal, the DC/DC converter (no. 4), and lastly the 12 V (no. 5) and 5 V (no. 7) voltage regulators.

The connection of the dash board diodes are not that different compared to the switches. They are also directly passed through to the PowerNode, but three of them are connected to the PWM-channels and one to an I/O pin.

Two actuators are controlled by this node, the throttle servo and the steering wheel MR-brake. The control signal to the throttle servo does not need any adjustment, but a 5 V voltage regulator has been fitted to supply the servo with power. As with Node CL, there are adapting circuits for the MR-brake controller card, but in contrast to Node CL, a card has actually been installed — it is mounted directly on the circuit board as seen in Figure 2.21.

The wheel node circuit boards (see Figure 2.22) have been prepared for five sensors and three actuators each, although some of them are not used in the front nodes.

The simplest sensor to adapt is the wheel angle encoder, i.e. the encoder signal is passed through to the PowerNode directly, without any circuits in between. The only component needed is the 5 V voltage regulator, which supply power to the encoder. The analog linear position sensor and the brake pressure sensor are also supplied by the same voltage regulator.

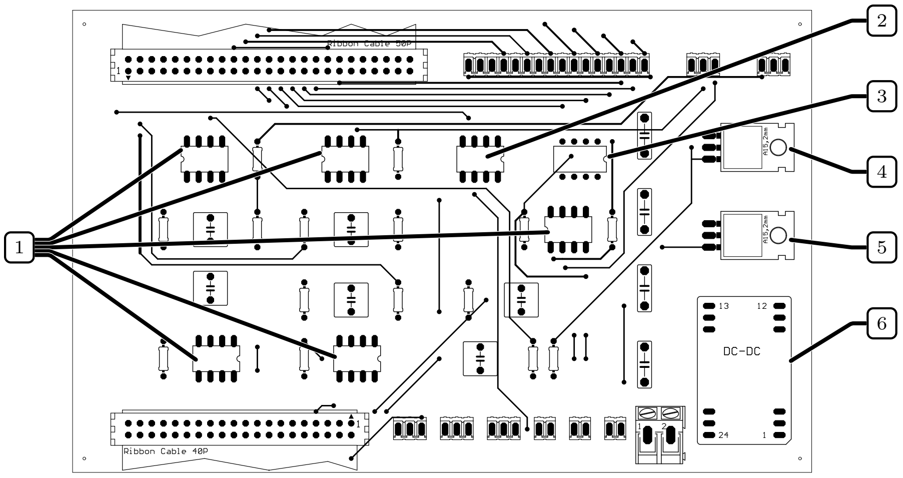


Figure 2.22. The adaptive electronic circuit board for the wheel nodes. The components are as follows; operational amplifiers (no. 1), relay (no. 2), optically coupled logic gate (no. 3), 5 V (no. 4) and 12 V (no. 5) voltage regulators, DC/DC converter (no. 6).

Both these analog signals are filtered, through the same type of filter used everywhere else, to reduce high frequency ripple. Do note that after the filter, the pressure signal is passed through an amplifier stage. The amplifier is needed because only 20% of the signal range is used — the sensor output is 0 to 5 V which corresponds to a pressure between 0 and 25 MPa, but according to [35] the pressure in the braking system will not exceed 5 MPa.

As mentioned earlier in this chapter, the rear nodes have an additional speed sensor fitted, which measures the speed by registering the change in a magnetic field. The sensor output is a very week sinusoidal signal with a frequency proportional to the angular velocity of the wheel. Since the frequency is the desired property to measure, a timer channel[41] on the PowerNode should be used, and the preferred input signal is a nice square wave shifting between 0 and 5 V. To accomplish that, the sensor output is first amplified by a factor of 10 inside an amplifier stage, and then passed through an optically coupled logic gate[42], which creates a discrete signal with the same frequency as the input signal. In contrast to all other circuits on the board, this logic gate is powered by the PowerNode.

The wheel and brake acutators connected to this node are controlled, via their motor control boxes, by two PWM-channels each. This is due to the fact that the control boxes have one input to run the DC motor in one direction and one for the other. No different form the other cards, the control signals are passed through a filter and an amplifier stage before leaving the circuit board. There is, however, one exception — the signal to retract the brake actuator is not amplified [35].

Lastly, also just implemented in the rear nodes, a relay has been fitted to control the park brake lock on the brake actuator motors (one for each actuator). The relay is connected similar to the relays used in Node CL. The only difference is the power supply — 24 V instead of 12 V.

[41]An I/O port which can, among other things, register the frequency of a signal.

[42]Schitt trigger HCPL2200, [10]

Chapter 3

Modifications

Although much effort had been put down during the re-configuration of the car at Luleå, some solutions have been found that need to be reviewed or modified. In this chapter, some of the more important ones are discussed, which all have the common aim to improve the overall system behaviour.

Both mechanical and electrical modifications have been performed on the car. First a description of the problem and how it affects the system is presented. This is followed by a presentation of the chosen solution.

3.1 Steer Actuator Joint

In the original version of the car, all of the wheel actuators were joined to the spindles with a ball-and-socket joint, which allowed the outer part of the actuators to twist. Since it is a ball screw actuator, the length is controlled by a motor acting on a thread inside. Turning or twisting the inner part with respect to the outer (without the motor running) will produce the same result as when one screws a nut on a threaded bolt. This could be seen as disturbance or back-lash in the control system.

The simplest solution for this is to replace the ball and socket mount with a universal joint. In Figure 3.1 the old ball-and-socket joint (to the left) is seen together with the new one (to the right).

Since no commercially manufactured universal joints could be found that satisfied the requirements on dimensions, the joints were manufactured by the University workshop. In Figure 3.2 two views of the 3D model of the joint, made in Pro/ENGINEER[1], are seen. This model was the base, from which manufacturing drawings were made (see Appendix E). Please note that no stress calculations have been made on the joints. Normally, this should for course be included, especially for a safety critical part like this. However, after a discussion with the experienced personal at the workshop, the conclusion was made that the material choice and thickness should be sufficient for the time being.

[1]A CAD (Computer Aided Design) software package provided by the company PTC (`http://www.ptc.com/`).

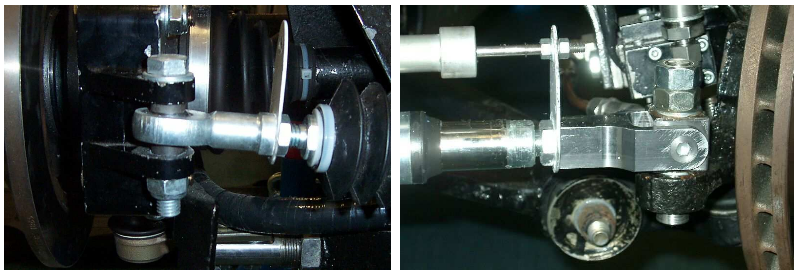


Figure 3.1. The modified steer actuator end joints - the old ball-and-socket joint (left) and the new universal joint (right).

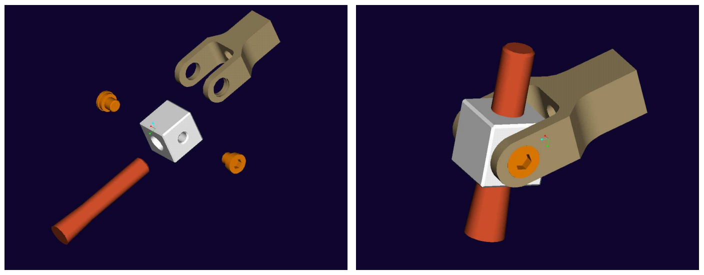


Figure 3.2. An exploded (left) and assembled (right) view of the manufactured universal joint. The 3D model of the joint was made in Pro/ENGINEER.

3.2 Front Wheel Encoders

All wheel encoders had originally a resolution of only 10 bit, but it was soon discovered not to be enough. So, new 14 bit encoders were purchased, but for some reason, only the rear wheel encoders were actually fitted at that time. This left the front encoders unchanged, which needed to be corrected.

Also, the encoders are mounted on the upper lever arm[2] of the front wheels, and the encoder shaft points downward and meets a rod welded to the spindles (see Figure 3.3). When the suspension moves up and down, the rod and the encoder shaft moves in respect to each other. Earlier, the rod and the encoder were connected with a piece of gasoline tubing to allow for this movement. However, this tube could flex significantly, which introduced disturbances in the encoder signal.

[2]Swedish: länkarm

One way to correct this problem is to move the encoder below the upper lever arm and connect it to the spindle using some kind of linkage, similar to how the rear wheel encoders are fitted (see Figure 2.17). Another way is to use some other type of connection.

The first solution might be better because it can be difficult to find a connection that has all the degrees of freedom, i.e. axial, radial, and angle displacement, to the extent that is needed. On the other hand, it requires a quite large engagement in the car to manufacture the linkage and the encoder mounting, and this was beyond the scope of this project.

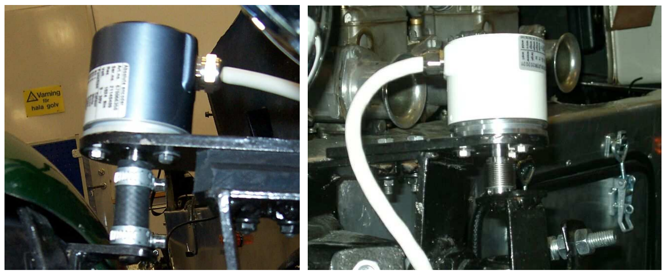


Figure 3.3. The front wheel encoders. The old 10 bit encoder with the gasoline tube connected to the spindle is seen to the left, and to the right is the new 14 bit encoder with bellow coupling.

Instead, the second solution was chosen and several different couplings have been investigated. It were found that quite a few couplings allowed the required degrees of freedom and among these were the curved-tooth gear coupling[3] and the bellow coupling[4], but none offered the extent of movement needed.

On the other hand, the springs in the wheel suspension have been tightened to a maximum (probably done when this problem was first encountered). In practice, this implies that the suspension will not move at all during normal driving conditions, and therefore release the demands on coupling movement (this also implies the car will not be very comfortable when driven).

The conclusion was to go for another coupling, despite that the requirement of extensive movement was not fulfilled. Here, the curved-tooth gear coupling should have been chosen, but instead a pair of bellow couplings were fitted, as they were found among some spare parts to car.

3.3 Wheel Actuator Control Boxes

The housing for the wheel nodes were originally pretty crammed. Not only did they house the PowerNodes and the adaptive electronic circuit boards, all the

[3]Swedish: bågtandskoppling
[4]Swedish: bälgkoppling

actuator control boxes were also fitted inside (see Figure 3.4). As the control boxes generate a fair amount of heat[5], and probably a lot of electrical noise, they had to be moved.

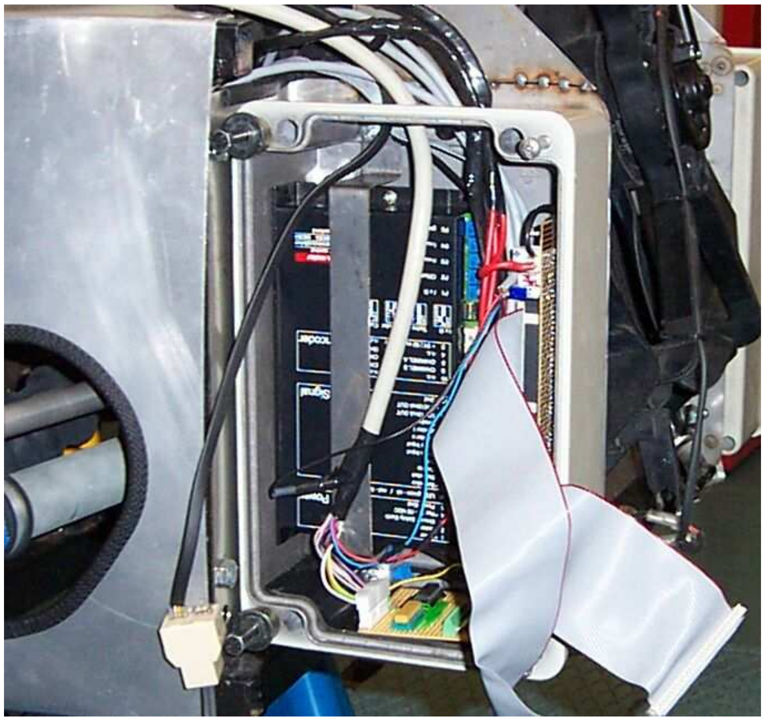


Figure 3.4. The Node FR housing before the actuator control boxes where moved in front of the radiator

The best solution in our opinion was to locate them as close as possible to the actuator they control, i.e. brake and steering actuators. As there are not much free space in the car where the boxes could be moved, the positions below were the only practical alternatives;

Rear nodes A fair amount of space could be found just behind the batteries. All four boxes could be mounted with a reasonable distance to the actuators (see Figure 2.18).

Front nodes After some investigation it appeared to be enough room just in front of the radiator fan, suitable for the four boxes controlling the front wheels (see Figure 2.5).

[5]Apparently the control boxes in the front nodes generated so much heat that the PowerNode overheated and ceased to function.

With these locations some kind of additional housing to protect the control boxes were needed, since the electrical connections otherwise would be unprotected. However, most of the other X-by-Wire equipment is at the present state unprotected, so finding or designing a protective housing for the control boxes alone, would not increase the system endurance by much.

Since suitable locations had been found, means of attachment had to be constructed. Using Pro/ENGEINEER, 3D models and manufacturing drawings (see Appendix E) of appropriate attachments where produced and handed in to the University workshop for fabrication. In Figure 3.5 and 3.6 the 3D models of the attachments are seen.

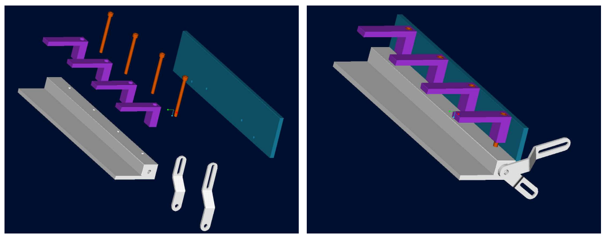


Figure 3.5. Two views of the 3D model of the front wheel control boxes, one explodes view (left) and one assembled (right).

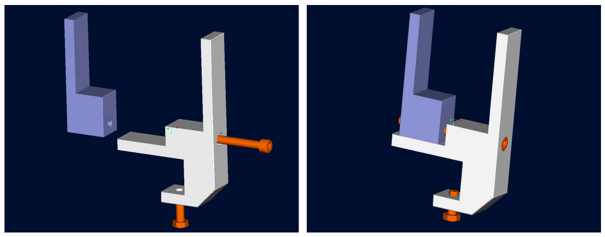


Figure 3.6. The 3D model of the rear wheel control boxes, one explodes view (left) and one assembled (right).

3.4 Wheel Nodes Circuit Boards

The wheel node circuit boards had to be reviewed, due to a number of reasons. First, as mentioned earlier in this chapter, the front wheel encoders had been replaced by another type with higher resolution. Second, the speed sensors at the rear wheel spindles had never actually been connected into the nodes and to do that, new components where needed. Third, the old rear wheel node boards had a circuit fault — the PWM signal that supposed to retract the piston in the brake actuator, was connected directly to ground.

Instead to continue to add and repair the old circuit boards, a new layout was designed. To save time, the old layout was used as a template. Only small modifications were done, in order to adapt the added equipment and take care of the prior faults. The same board layout is used in all wheel nodes, although all components are just utilized in the rear nodes. This was made to simplify for a prospective addition of sensor in the front nodes, like speed sensors for example.

The circuit boards were manufactured in the University workshop — in Figure 3.7 the milling of the connection wires is seen.

For the complete circuit diagram of the board, please refer to Appendix C, and in Appendix D a description on how to connect the actuator and sensor wires is found. For a review of the board and its components, see Section 2.4.

Just before the printing of this report, a fault in the circuit board design was discovered. The 2.2 kΩ resistor used for the pressure sensor had been misplaced — instead of being connected in parallel between the output signal and the 5 V power input, it was put in series with the power input. However, it is possible to connect the sensor to the board despite this error (see Appendix D for details).

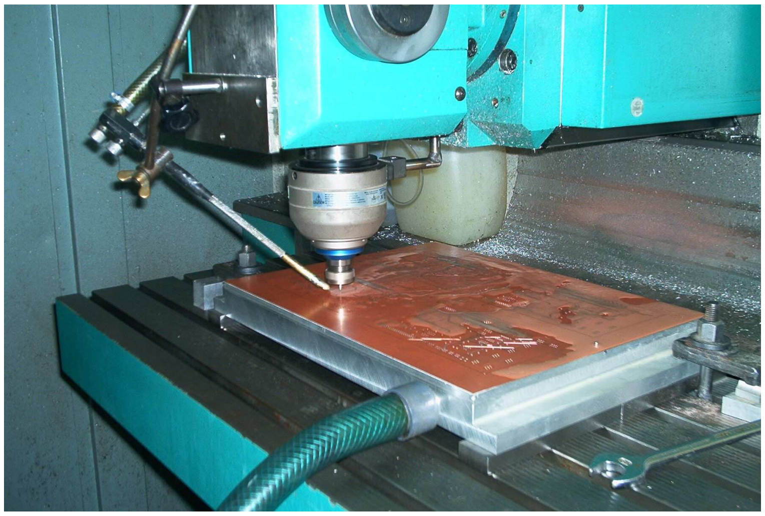


Figure 3.7. The milling of wire connections on the wheel node circuit boards.

Chapter 4

Synthesis

Until now, only the hardware installed in the car has been discussed, and nothing has been said about how to make everything work together as a whole. The glue to tie everything together is the algorithms used in the distributed real-time controller network. The network which not only renders the engineer almost endless possibilities to control how the car should behave and feel when driven — it also has drawbacks due to the increased complexity of the system that follows.

This chapter starts out by looking at some possibilities, as well as drawbacks and safety issues, that an X-by-Wire system have compared to a "normal" mechanical system. In addition, demands on the systems involved are specified throughout this chapter. These demands will be needed in Chapter 5.

4.1 Possibilities and Drawbacks

In an X-by-Wire system, the dynamics can be completely altered in software. All that is needed, in principle, is to write an algorithm telling the system what it should do, and when. In a car, this could be;

Using optimal wheel angles. Today, all cars have toe-angles[1] built into the wheel suspension to control the stability in acceleration or heavy break manoeuvres. In all other cases, toe-angles are just a drawback since they decrease the expected life time of the tires. To be able to dynamically control when to use toe-angles, and when not to, could considerably reduce the owners tire cost.

Parallel manoeuvres. Under certain conditions, a lane change on the freeway or parking for instance, it could be desirable to move sidewise without having the car turning.

Stability control during strong side wind. When driving a car in strong side wind, the driver constantly has to compensate the wind forces that act on

[1]A small angle on the wheel so that two wheels on an axle are not completely parallel to each other.

the car in order to keep the car on the desired path. This could instead be done automatically by the system.

Skid control. Some of the new cars today already have skid control systems (like the DSTC[2] system in Volvo XC90), but they all try to stabilize the car by braking only. The performance could probably be improved by using both steering and braking with an X-by-Wire system. The four wheel steering also makes it possible to maintain control of the vehicle even if the front wheels are locked in a panic brake situation.

All things presented in the list above cannot be realized in this car, in its present state. However just small additions in hardware could make these things (and more) possible.

The primary drawbacks in computer based controller systems regards reliability and safety. These issues make it difficult to guarantee correct operation in all situations. Pure mechanical systems have a big advantage in that respect — faults are often both easier to spot at an earlier stage in the design process, and fewer in quantity. Figure 4.1 points out some of the areas where safety issues have to be considered, in addition to the pure mechanical ones.

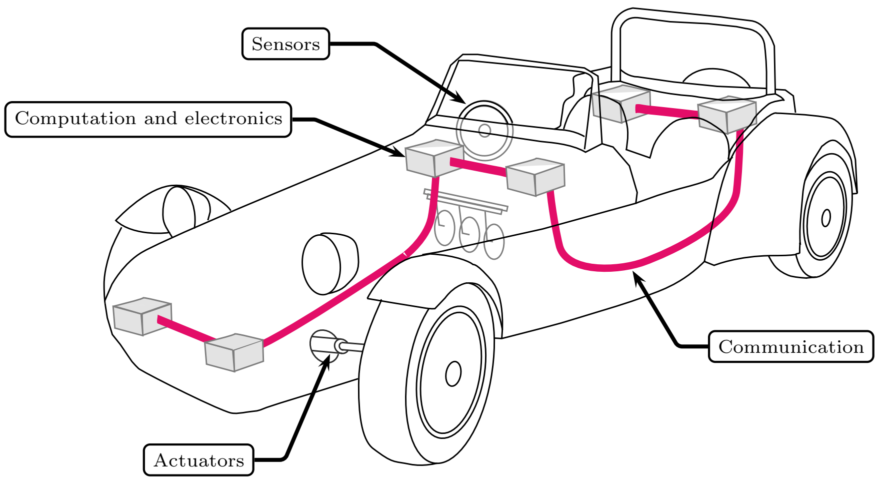


Figure 4.1. Possible source of faults in the X-by-Wire system (drawing made by Katja Tasala).

Numerous of incidents have happened over the years, which all are related to hard or software faults in the computer based controller system:

In a computer controlled radiation treatment equipment (the Therac-25), six accidents happened (where three people died of radiation injuries) during the years 1985 - 87. The reasons were faults in the

[2]Dynamic Stability and Traction Control

user interface, a 6 bit counter where set to 0, and a hardware lock had been removed [40].

In 1992 a Boeing 767, belonging to Lauda-Air, suddenly changed the jet drag direction during a fight [40].

Although it is not possible to guarantee a flawless system, the chance of stability and correct functionality can be increased by using redundant[3] components. Doing that, though, presents new problems like choosing which component to trust in a fault situation and which action to take if one or several of the components fail. Again, it is the engineer who has to construct algorithms to handle that.

4.2 Controller Structures

The car presents opportunities and drawbacks not found in any of the commercially available cars today. The wheel angles and brake pressures can be controlled individually at each wheel, without the need of driver input. In fact, with some small additions one could actually remove the driver entirely, and steer the car remotely. The same contingencies[4] also apply to the throttle valve opening and the clutch. The only thing you still need to do manually in the car is shifting the gears.

In order to control all these parts and make use of the performance built into the car, controllers are needed. These controllers must be stable in every situation, even if a sensor fails. To guarantee stability in a situation where a sensor gives incorrect readings an open-loop controller is the safest alternative since it stays unaffected. It can however be hard, or even impossible, to construct such a controller if the system is non-linear or otherwise difficult to model.

4.2.1 Wheel Angle Controller

The wheel angle controllers job is to keep the wheel angles synchronized with a commanded value, i.e. work as an angle servo. In addition it also have to keep track of where the other wheels are when moving. A very important factor for the cars stability is the aforementioned toe-angles. This makes it imperative for the controller to, at all times, keep the wheels moving correctly with respect to each other.

The main demand on a wheel angle controller is naturally stability. It has to be, in every situation, stable since an oscillating wheel would surely result in a violent crash.

In this particular application it is also important for the controller to be tolerant towards model errors since the four wheels all have different parameters[5]. The parameters of a wheel can also change substantially when driving, if for instance the road changes from tarmac to gravel.

[3]Two or more components doing the same job.

[4]Swedish: möjligheter

[5]The electrical motors have different top speeds and the actuators have different friction.

4.2.2 Brake Controller

On a traditional car the pressure in the brake system is directly proportional to the force that is applied to the brake pedal. It is the brake controllers mission to accomplish this by controlling some sort of actuator.

When constructing the brake controllers, both speed and stability are important factors. The speed requirement is important since the latency between pedal force application and pressure buildup must be as short as possible. As a rule of thumb this latency can be no more than 100 ms.

To make the design stable in all situations the rule of thumb has, traditionally, been to construct an open-loop controller. In the case of the braking system implemented in the car, this is not possible since the brake actuator has very high static friction[6]. This makes an open-loop controller impossible since an applied force on the piston is not directly proportional to the pressure.

4.3 Replicated subsystems

A replicated subsystem is defined as two identical systems with identical input. It is, for example, used to minimize errors resulting from power outages which could prevent a processor from completing its task. A redundant sensor is a special case of a replicated subsystem, with only one component. The replicated subsystem can contain any number of components.

In software there are a couple of replicated subsystems;

- The algorithm that calculates the wheel angles are implemented in software on both center nodes and the algorithms are fed by the same input from the network.
- Brake values are calculated in both center nodes.

For more information on the software, please refer to Chapters 5 and 6.

Hardware-wise there are also some replicated subsystem in the form of two sensors measuring the same value. These can be found in the next section.

4.4 Redundant Sensor Handling

Some of the sensors in the car are doubled to make the readings more reliable. The replicated sensors are;

- The steering wheel angle is measured by two independent encoders and each encoder is connected to one of the center nodes.
- There are two identical sensors that measure the position of the brake pedal and each sensor is connected to one center node.
- The wheel angles are measured in two ways; directly by an absolute digital encoder and indirectly by measuring the length of the wheel angle ball screw.

[6]The force that must be overcome to start moving an object.

When using redundant sensors more difficulties arise. Merging sensor values is a research area in itself which is called *Sensor Fusion*. Some of the problems in this area are:

- How can the values be merged so that the result is *in all cases* better than it should have been if using only one sensor.
- If the readings from a redundant sensor differ, which is correct?

More on this subject can be found in [7].

4.4.1 Wheel Angle Sensors

The two sensors that measure the wheel angle on one wheel do not have a linear relationship to each other depending on the geometry of the suspension. This means that the values have to be adapted to each other. One way to do that is to look at the geometry of the wheel suspension and construct an algorithm that takes either value and translates it to the other. This is however cumbersome since it involves a whole lot of complex algebra due to the complicated geometry of the suspension. A more practical solution is to create a lookup table to translate between the values.

The dynamics of the steering, including actuator, motor and motor control box, make it easy to model the behavior of the wheel. Since the input to the motor control box is a reference value for the motor speed, a simple integrator with delays taken from the data sheets of the motor control box and motor [25, 27] is a fairly correct model (see Section 5.1 for a more detailed description of the model).

The model is used when comparing the two sensor values. In reality three values for the wheel angle can easily be found; two measured and one calculated using the output of the model when it is fed all earlier control signals. This makes it possible to spot single errors[7] by invalidating the sensor that deviates too much from the calculated value. It is also possible to detect other errors; if for example the two sensor readings are about the same, but differs a lot from the calculated value, there is probably something wrong with the actuator or the motor.

The traditional way to achieve this kind of sensor fusion is to design a Kalman filter. But since the wheel angle subsystem has almost no dynamics it is not needed and this simpler approach can be used instead.

4.4.2 Steering Wheel and Brake Pedal Sensors

When measuring signals that are not controlled by the system, the task of sorting out an erroneous sensor is more difficult. A predictor cannot be constructed and only a few properties of the signals can be defined. For example; a sensor reading that measures the steering wheel angle cannot change too quickly and it cannot exceed some mechanical limits.

Using this a failing sensor can be detected if it changes rapidly but not if it has a constant (or slowly changing) offset. In addition there is no way, in most cases,

[7]When one of the sensors fail.

of detecting which one of the sensors that is failing, just that something is wrong. This makes these systems suitable for detecting errors, but they cannot be used to correct errors.

4.5 Non-redundant Sensor Handling

Without the power of redundant sensors, the possibility to detect errors is pretty slim. The only possibility left is to check if the sensor value exceeds some boundary values, either in the time or in the frequency domain.

The sensors in the car that fall into this category are;

- Throttle pedal sensor
- Clutch pedal sensor
- Brake pressure sensor

These can all be considered to be less critical than the redundant sensors discussed above[8], since even if one of these should fail and cease to function the driver would still be able to stop the car without danger.

4.6 Driver Feedback Control

The purpose of this system is to make the car more comfortable to drive. It is supposed to create the sensation[9] that an ordinary car gives the driver.

When one drives a car, one can feel the forces that are put on the front wheels through the steering wheel. One can also feel the pressure in the braking system when depressing the brake pedal.

These are both very important factors when driving a car because it tells how the car is handling and where it is going. In an X-by-Wire car this must be simulated using actuators that brake or induce forces in the steering wheel and the brake pedal.

In the Sirius 2001 Concept Car the means for driver feedback are two MR-brakes. This implies that only friction and no forces can be applied which make the possibilities limited.

If the amount of feedback, i.e. the applied friction, should depend on some external value (for example the error between the commanded wheel angle and the current wheel angle) there could be cases where the brake could lock up the steering wheel or brake pedal (example; if the brake pedal is depressed hard and then released the feedback brake could lock the pedal in the depressed position). This is naturally not the desired behavior. This restriction reduces the possibilities of a realistic driver feedback even more.

[8]Except for the brake pressure sensor, but the system was originally designed for traditional open-loop brake controlling, i.e. this sensor was never planned to take part in a critical system.

[9]Stiffness in the brake pedal and the forces from the road that can be felt in the steering wheel.

All of those impairments really only leaves one realizable solution; the applied brake friction should be proportional to the angular velocity of the steering wheel respectively the speed which the brake pedal is depressed with. This is not really a realistic feedback, but it is one solution which guarantees that the steering wheel or brake pedal will not lock up in any position.

4.7 Summary

This chapter has outlined the most important properties that an X-by-Wire system needs to have. Some of the advantages over conventional cars have also been discussed.

Some demands on the controller structures have also been defined and these will come to good use in Chapter 5.

Chapter 5

Implementation

In the previous chapter, the properties of an X-by-Wire system in general, and the Sirius 2001 Concept Car in particular, were defined. In this chapter these properties and demands are used to design controller structures for the individual subsystems.

5.1 Wheel Angle Controller

The basic design goal behind this controller was to make as much use of the power in the actuators as possible, while maintaining the stability of the system. Another demand that needed to be fulfilled was that, when moving, the wheels must move coordinated, even if they have different properties and commanded angles.

A “bang-bang” controller fulfills the basic demand, because it uses the largest available control signal [6]. This makes the actuators move as fast as possible at all times.

The bang-bang controller is, by design, very sensitive to noise in the measured signals and can easily oscillate. To remedy this another controller is often used for small errors. In this case a bang-bang controller was used for large errors and a PI-controller, which was designed using Ziegler-Nichols [5], was used for small errors.

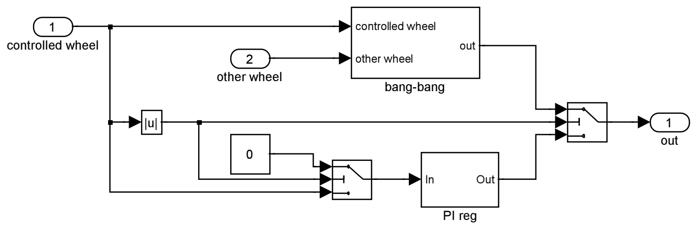


Figure 5.1. Simulink model of the wheel angle controller.

The wheel angle controller can be found in Figure 5.1. Note that the PI-controller is fed a zero input until it is switched in to prevent the integrator from winding up. The “other” input to the bang-bang controller is the error from the other wheels. This will be further discussed below.

To construct the two controllers a model of a wheel is needed.

5.1.1 Wheel Angle Subsystem Model

The system that needs to be controlled when changing the wheel angle consists of;

- Motor control box
- Electrical motor
- Ball screw actuator
- The linear sensor that measures the length of the ball screw
- Wheel angle encoder
- Software in the PowerNodes
- The network

The software in the PowerNodes generates PWM-signals that are fed to the motor control boxes. This makes the motor turn with an angular velocity that is directly proportional to the PWM-value since the control box and the motor are themselves a closed loop system. This removes nearly all of the motor dynamics and simplifies the model a lot. When the motor turns the length of the ball screw is altered and this in turn makes the wheel twist.

A fairly correct model for all this is a simple integrator with some delays in it. This is reasonably correct, since the system (from PWM-value to angle alteration) has nearly no dynamics and the PWM-value should be proportional to the wheel angle velocity.

The amount of delay can be found by looking through the data sheets for the different components [1, 8, 25, 27, 30, 38, 41];

Motor control box In the data sheet the bandwidth is found to be 2.5 kHz $\Rightarrow$ $\frac{1}{2500} = 4 \cdot 10^{-4} = 0.4\,\text{ms}$.

Motor The data sheet states that the time constant is 5 ms.

Balls crew actuator The balls crew is completely rigid so the time constant is zero.

Linear sensor The resistance changes instantly when the length of the sensor changes. The PowerNode then samples this value, which adds a delay. The data sheet for the Motorola PowerPC processor states that sampling takes at least 14 QCLK, and the QCLK is 2 MHz $\Rightarrow$ $7\,\mu$s.

Encoder The data sheet states that the codes coming from the encoder can change with a frequency of 100 kHz $\Rightarrow \frac{1}{100000} = 1 \cdot 10^{-5} = 10\,\mu$s.

Software algorithms This will take no longer than 5 ms.

Network The delay of messages on the network depends on the TDMA round (see Chapter 6) which was chosen to be 10 ms. This delay will only affect the messages that need to be transferred over the network.

In conclusion, the system that needs to be controlled, from PWM-value to wheel angle, has a delay of roughly;

$$4 \cdot 10^{-4} + 5 \cdot 10^{-3} + 7 \cdot 10^{-6} + 10 \cdot 10^{-6} + 5 \cdot 10^{-3} < 20\,\text{ms}$$

plus an additional 10 ms for values that has to travel the network.

So an integrator with a time delay of 20 ms would be a reasonably good approximation for this system. The delay was chosen high since the practical resolution in the finished system is 10 ms since the controller is updated every second TDMA round (refer to Chapter 6 for more information).

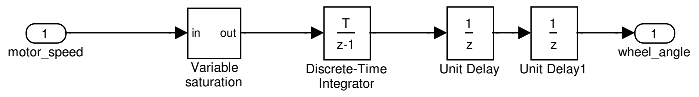


Figure 5.2. A somewhat simplified model of a wheel angle system.

A Simulink model of this can be seen in Figure 5.2 where the block called "variable saturation" is a block that restricts how fast the wheel can move to model friction and other disturbances. A more complete view of two wheels can be seen in Figure 5.5 where the delays of the network messages can be seen.

5.1.2 Wheel Angle Predictor

The simple model that was defined in the last section is used to verify the sensor readings. If this model is fed the same signals as the actual wheel, it would generate a good estimate of the wheel angle.

This predicted value is used to verify that the values read from the two wheel angle sensors are correct. If the sensors deviate too much, they are invalidated.

5.1.3 The Bang-Bang Controller

The bang-bang controller type was chosen because it makes as much use of the hardware as possible by always using the largest possible control signal.

To make the wheels move synchronized the control signal that the bang-bang controller would generate was adjusted so that the wheels would reach their commanded angle at the same time. This was implemented by taking the wheel with the greatest difference between commanded and actual angle and calculating how much time it would take for this difference to vanish if the wheel traveled with its maximum speed. This time was then used to calculate the speed by which the current wheel would have to move in order to reach its destination at the same time.

Introduce the variables;

$$\begin{array}{rcl} \alpha, \beta, \phi, \theta & : & \text{Wheel angle errors for the four wheels} \\ \omega_\alpha, \omega_\beta, \omega_\phi, \omega_\theta & : & \text{Angular velocities for the four wheels} \end{array}$$

Using this, the time that a wheel takes to reach its destination, i.e. when the wheel angle error equals zero, can be calculated as;

$$\tau_\alpha = \frac{\alpha}{\omega_\alpha},\ \tau_\beta = \frac{\beta}{\omega_\beta},\ \tau_\phi = \frac{\phi}{\omega_\phi},\ \tau_\theta = \frac{\theta}{\omega_\theta}$$

The goal is that these times should all be equal to the largest time;

$$\tau = \frac{\alpha}{\omega_\alpha} = \frac{\beta}{\omega_\beta} = \frac{\phi}{\omega_\phi} = \frac{\theta}{\omega_\theta} = \max\{\tau_\alpha, \tau_\beta, \tau_\phi, \tau_\theta\}$$

This is accomplished at the wheel with the wheel angle error α like;

$$\begin{array}{lcl} \max\{\tau_\alpha, \tau_\beta, \tau_\phi, \tau_\theta\} = \tau_\alpha & \Rightarrow & \omega_\alpha = \omega_{max} \\ \max\{\tau_\alpha, \tau_\beta, \tau_\phi, \tau_\theta\} = \tau_\beta & \Rightarrow & \omega_\alpha = \frac{\alpha}{\beta} \cdot \omega_\beta \\ \max\{\tau_\alpha, \tau_\beta, \tau_\phi, \tau_\theta\} = \tau_\phi & \Rightarrow & \omega_\alpha = \frac{\alpha}{\phi} \cdot \omega_\phi \\ \max\{\tau_\alpha, \tau_\beta, \tau_\phi, \tau_\theta\} = \tau_\theta & \Rightarrow & \omega_\alpha = \frac{\alpha}{\theta} \cdot \omega_\theta \end{array}$$

And similarly for the other wheels.

Using this technique, all wheels will reach their destination at the same time, even if they have to travel different lengths and have different properties. It does however involve some calculations that can be eliminated.

Suppose that all four wheels have the same top speed. This implies that the wheel which has the largest angle error also will need the largest time to reach its destination which in turn means that instead of comparing the time it would take for the wheels to reach their destination one could compare the angle errors directly. For the wheel with wheel angle error α this means that;

$$\begin{array}{lcl} \max\{\alpha, \beta, \phi, \theta\} = \alpha & \Rightarrow & \omega_\alpha = \omega_{max} \\ \max\{\alpha, \beta, \phi, \theta\} = \beta & \Rightarrow & \omega_\alpha = \frac{\alpha}{\beta} \cdot \omega_{max} \\ \max\{\alpha, \beta, \phi, \theta\} = \phi & \Rightarrow & \omega_\alpha = \frac{\alpha}{\phi} \cdot \omega_{max} \\ \max\{\alpha, \beta, \phi, \theta\} = \theta & \Rightarrow & \omega_\alpha = \frac{\alpha}{\theta} \cdot \omega_{max} \end{array}$$

This eliminates the need to calculate the wheel angle velocity. It will also protect the system if a wheel is stuck, since the other three wheels will still move (although somewhat slower).

The assumption that the wheels have the same top speed can be made because if a wheel has significantly lower top speed for a short period of time, for example

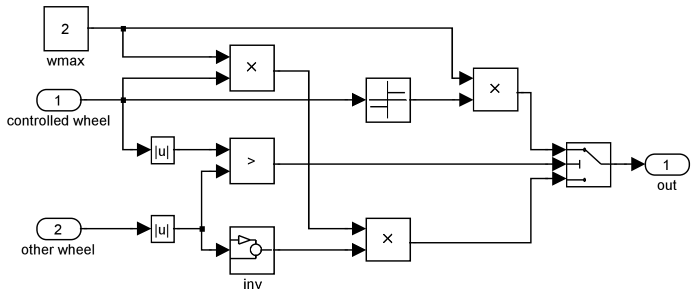


Figure 5.3. Simulink model of the bang-bang controller.

due to a puddle of mud, it is taken care of by the high sample rate. If it has lower top speed for a long period of time, it is probably something wrong with the wheel and it is more important for the other wheels to reach their destination quickly.

A Simulink model for the bang-bang controller for two wheels can be found in Figure 5.3. In the model the controlled wheel angle error is first compared to the largest of the other wheel angle errors. This comparison decides how the wheel angle actuator should move; if another wheel has the largest angle error the speed is set according to the rules above, otherwise the speed is set to the largest available control signal (ω_{max}) multiplied with the sign of the angle error (to make the wheel turn in the right direction). The model can easily be extended to handle four wheels by replacing the "other wheel" signal with the largest angle error of the other wheels.

5.1.4 The PI Controller

To remedy the bang-bang controllers poor stability it is deactivated for small wheel angle errors, instead a PI-controller is used. Ziegler-Nichols method [5] was used to tune the parameters for this controller.

When tuning a controller using Ziegler-Nichols the steps below generate the initial values.

1. Create a closed loop system with only proprotional control.
2. Increase the proportional gain until the system starts oscillating with a constant amplitude.
3. Note the gain and period of oscillation.

When this was used on the wheel model presented above in Figure 5.2, the oscillations began with a period of $T_0 = 0.1$ s when the gain was $K_0 = 62$.

With these values the Ziegler-Nichols rules give the controller parameters listed below;

$$\begin{array}{lll} \text{P} & : & K = \frac{K_0}{2} = 31 \\ \text{PI} & : & K = 0.45 \cdot K_0 = 27.9,\ T_I = \frac{T_0}{1.2} \\ \text{PID} & : & K = 0.6 \cdot K_0 = 37.2,\ T_I = \frac{T_0}{2},\ T_D = \frac{T_0}{8} \end{array}$$

when using a controller on the form;

$$u(t) = K(e(t) + \frac{1}{T_I}\int_{t_0}^{t_1} e(\tau)\,d\tau + T_D\frac{d}{dt}e(t))$$

where $e(t)$ denotes the wheel angle error as a function of the time t.

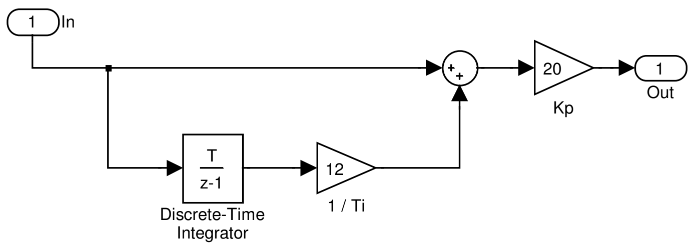


Figure 5.4. Simulink model of the PI controller.

From these values the PI controller was chosen and the amplification was lowered somewhat to enhance the stability[1]. A Simulink model of the PI-controller can be seen in Figure 5.4.

5.1.5 Result

A model of the final system for two wheels can be seen in Figure 5.5. Note that the two wheels can be fed different commanded angle values (the two steps to the left). The two delays shown represents the delay when sending messages across the network.

The model was tested by choosing different commanded values for the two wheels and setting the disturbances in the "variable saturation" block differently for the two wheels. The tests showed promising results and the wheel angles followed each other nicely even if the commanded values and/or disturbances where very different.

In Figure 5.6 a test run was made where one wheel was fed the commanded angle of 2 (solid line) while the other one was fed a commanded angle of 1 (dashed line). The variable saturation block was fed a white noise signal for both wheels in this run.

[1]The controllers speed is lowered due to this, but since it is only used for small errors this will not affect the overall performance much.

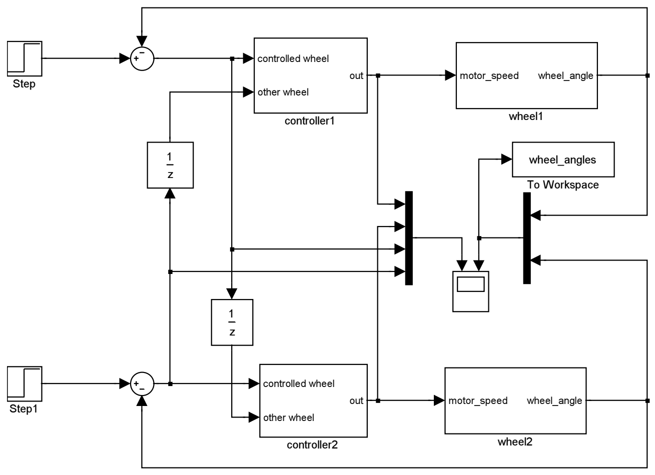


Figure 5.5. Simulink model which represents two wheels.

In Figure 5.7 the same commanded values as before were used, but one of the wheels was disturbed by a sinusoidal signal instead of white noise.

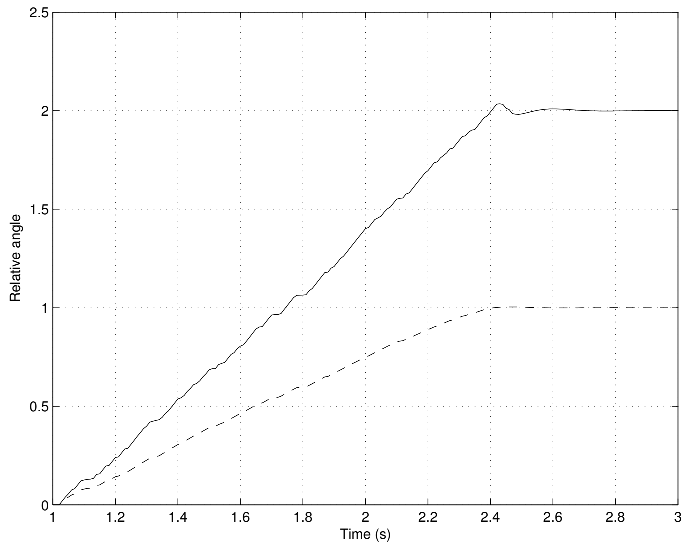


Figure 5.6. First test run of the wheel angle controller.

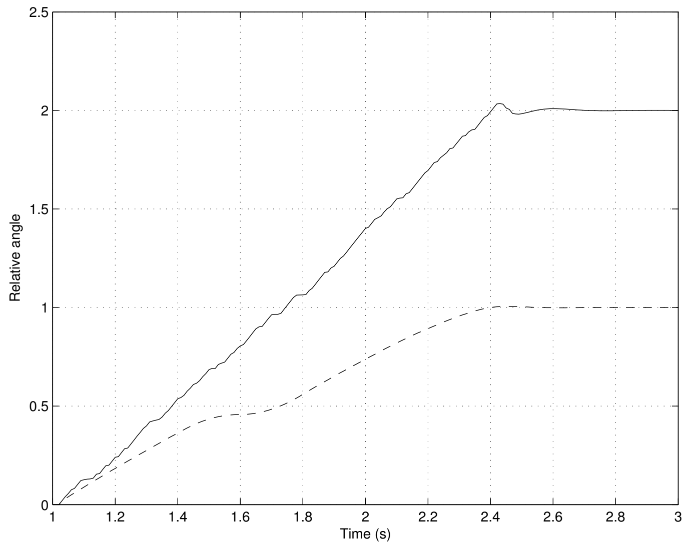


Figure 5.7. Second test run of the wheel angle controller.

5.2 Steer Algorithms

This section discusses the problem of translating a given steering wheel angle into commanded wheel angles. The algorithm plays a significant role in how the car is behaving, which make it important that this is a well designed algorithm.

Everything that is said below assume that the wheels all roll without slipping. This is of course far from the truth, but the results are nevertheless useful.

5.2.1 Ackermann Steering

When a car performs a turn the inner and outer wheels roll on different radii. To prevent the tires from skidding, the inner wheels must turn with a greater angle than the outer wheels. This is called Ackermann steering and is often measured in percentage of true (i.e. 100%) Ackermann. An explanatory sketch can be found in Figure 5.8.

Using 100% Ackermann the four wheel angles can be calculated as;

$$\begin{aligned}
\tan\alpha &= \tfrac{l-c}{r-\frac{b}{2}} \\
\tan\beta &= \tfrac{l-c}{r+\frac{b}{2}} \\
\tan\gamma &= \tfrac{c}{r-\frac{b}{2}} \\
\tan\delta &= \tfrac{c}{r+\frac{b}{2}}
\end{aligned}$$

when using the notation given in Figure 5.8.

Traditional cars never have true Ackermann because the wheel angles are always a compromise between stability and tire wear. In the car at hand, all wheel angles can be set independently of the others, which make true Ackermann an obvious choice.

5.2.2 Steer Angle Distribution

For a traditional two wheel steered car the center of rotation is always fixed to the rear axle. This is not the case for a four wheel steered car, where the center of rotation can be put anywhere on a line going through the middle of the car. It is also possible to control how the car is orientated during the maneuver.

If the steering angles on the front and rear axle are equal, the car can move sideways without rotating. This can be good for lane changing or obstacle avoidance since the car avoids rotating. The maneuver can be seen in Figure 5.9.

Another special case is when the center of rotation is set in the middle of the car. This lets the car turn with the shortest radius, and this is especially good for parking and maneuvering in tight places.

However, under normal driving conditions none of these two special cases are usable since the car behaves very differently from a conventional car, and the driver will have a difficult task just controlling the car. Instead some algorithm that steers the rear wheels with less extreme angles is needed. In such an algorithm the relationship between front and rear steer angles can be dependent on dynamic parameters such as the forward speed or the yaw rate.

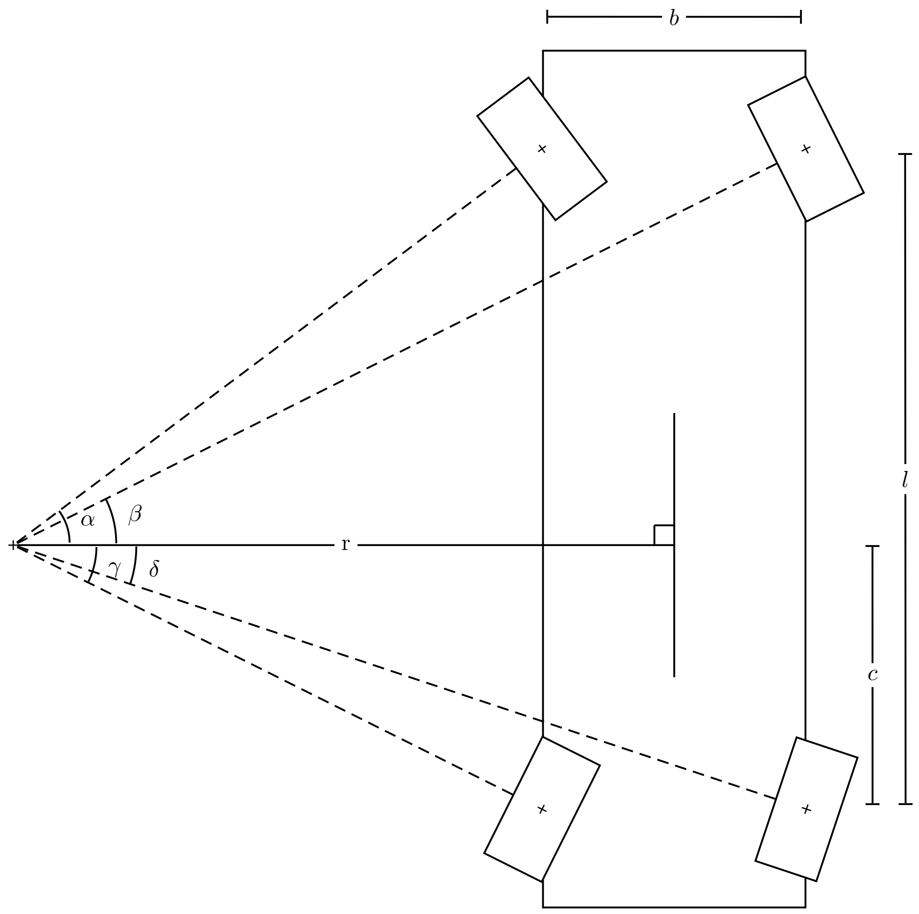


Figure 5.8. Explanation of true Ackermann Steering. Note the difference between α versus β and γ versus δ.

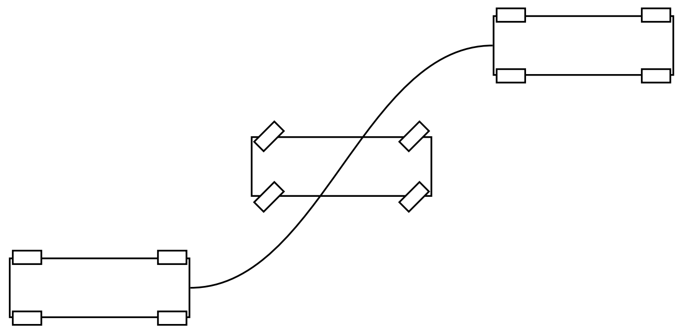


Figure 5.9. How a four wheel steered vehicle makes a parallel maneuver.

Introduce the variables;

δ_f	:	Forward steer angle.
δ_r	:	Rear steer angle.
C_f	:	Traction on the front wheels in [N/rad].
C_r	:	Traction on the rear wheels in [N/rad].
l_f	:	Distance between the mass center and the front axle.
l_r	:	Distance between the mass center and the rear axle.
m	:	Mass of the car.
V	:	Forward velocity.
$\dot{\theta}$	:	Yaw rate.

Sridhar and Hatwal [15] discuss five different steering models during a lane change maneuver;

A Rear steer angles are kept at zero resulting in a behavior like that of a two wheel steered car.

B The relationship between forward and rear steer angles involving the forward velocity with;

$$\delta_r = K \cdot \delta_f \text{ with } K = \frac{C_f l_f m V^2 - 2C_f C_r l_r (l_f + l_r)}{C_r l_r m V^2 + 2C_f C_r l_f (l_f + l_r)}.$$

If the front steer angles are specified this algorithm gives rear steer angles that are well adapted to the car.

C A model where the rear steer angle depends on the front steer angle and the yaw rate;

$$\delta_r = K \cdot \delta_f + C_1 \cdot V \cdot \dot{\theta} \text{ with } K = -1 \text{ and } C_1 = \frac{m}{2(l_f + l_r)}(\frac{l_r}{C_f} + \frac{l_f}{C_r}).$$

In addition to algorithm B this one takes the cars yaw rate into account to prevent the car from skidding.

D The rear steering depends on the product of the yaw rate and forward velocity;

$$\delta_r = C_2 V \dot{\theta} \text{ with } C_2 = \frac{m}{2(l_f + l_r)}(\frac{l_f}{C_r} - \frac{l_r}{C_f}).$$

Like algorithm C the yaw rate is taken into account when calculating the rear steer angles. This one has however a different, nonlinear, relationship since it depends on the product between forward velocity and yaw rate.

E The front and rear angles are individually and optimally controlled (hypothetical model).

Note that algorithm A through C give negative[2] values for the rear steer angles when the forward speed is low, and algorithm D gives positive values for all speeds. If the rear steer angles are negative, the center of rotation is placed inside the car. This will lower the minimum turning radius, thus making the car more maneuverable. If the angles are positive then the center of rotation is placed outside of the car, which will lower the yaw rate and therefore the risk of skidding.

Sridhar and Hatwal [15] come to the conclusion that model D has the best characteristics from the point of view of steering effort. It is also the only of the models that produces neutral steer characteristics. Models B and C both produce extreme under steer. However the only realizable four wheel steering model of the ones listed above would be B since the car has no yaw rate sensor.

The yaw rate could however be calculated by using the speed sensors, to measure the difference between the speed of the inner and outer wheels. This would imply that all wheels must roll without slipping, that assumption can only be made for small velocities [31] so the calculations will not produce a reliable value on the cars yaw rate.

5.3 Brake Force Controller

The demands on the brake controller is mainly stability. The function of the brake system must also stay unaffected even if a sensor should fail. Therefore it is often common to use an open loop controller. However, the brake actuators in the car have so high static friction that this is not possible. To design a usable system the controller must be able to overcome this friction and at the same time guarantee stability.

Apart from the static friction the system is very simple. The control signal is sent as a PWM signal to the brake motor control box. The box is set for current control so the PWM signal is proportional to the current and therefore the torque on the motor axle. This torque is transferred to the piston via a gear box. When the piston moves the pressure is built up in the braking system and the brake pads are pressed against the brake disc.

[2]If the front wheels turn left, the rear will turn right.

One possible solution to this problem that maintains the open loop structure is to generate the control signal as a linear combination of the commanded force and its derivate. So if $r(t)$ is the commanded force and $u(t)$ is the control signal that is fed to the brake motor control box as a PWM signal, the expression would look like this;

$$u(t) = A \cdot r(t) + B \cdot \frac{d}{dt} r(t).$$

Where A and B are constants.

This design will have problems if the brake pedal is depressed or released slowly (i.e. during normal driving conditions). So it is not really usable for this system.

The open loop design must be sacrificed in this case, and a controller using the brake pressure as feedback is used. This is a bad choice since the brake pressure sensor is non redundant, and since it is an analog sensor it is vulnerable to noise, but unfortunately it is the only choice.

5.4 Braking Algorithms

The brake algorithm that is implemented in the car is a very simple one with a static brake distribution that always maintains a fixed ratio between the front and rear axle. The possibilities are however almost endless for more advanced algorithms.

One example is to distribute the brake force differently on the outer and inner wheels when cornering. The outer wheels have higher contact forces so they can be braked harder than the inner wheels. A car that implements this and is available today is the top of the line Mercedes-Benz SL 500 coupe/roadster which has a system called Sensotronic Brake Control. This system is reviewed in more detail in [13].

Chapter 6

Schedule

This chapter outlines the steps involved in scheduling this particular real time system. This involves defining subsystems, tasks and messages.

6.1 The Time-Triggered Architecture — the TTP/C Protocol

Before describing the schedule, a short introduction to the TTP/C is appropriate. For a more thorough explanation and the history of TTP/C [22] is recommended.

TTP/C is a communication system of class C, and must therefore be strongly deterministic. This means that the behaviour of the system must be known beforehand, and some rules must be set up for it. These rules should include how and when both communications and computations are made.

All the rules put together form the schedule.

6.2 Subsystems

A subsystem can be seen as a set of tasks, or functions, that all collaborate to achieve a more complex function. In a TTP/C cluster, a subsystem can be completely replicated, partially replicated, or non-replicated. A replicated subsystem is run by several nodes in the cluster, and this makes the system dependable even if a node should fail.

In an X-by-Wire application it is logical to divide the system into steering and speed controlling subsystems. In the car, all of the nodes must run both these subsystems since they are all involved in controlling both steering and the speed.

In addition two other subsystems, supervision and calibration, have to be defined to make the car more dependable and easier to maintain and setup. These subsystems are also run on all nodes, naturally since all nodes have sensors that need calibration and it is important to supervise all nodes.

Finally a subsystem that is responsible for driver feedback is defined. This subsystem is only run on the two center nodes.

Table 6.1. The subsystems and their responsibilities.

Subsystem	**Center nodes**	**Wheel nodes**
Steering	Read steering wheel Calculate wheel angles	Read wheel angle Turn wheel
Speed controlling	Read brake pedal Calculate brake values Read clutch pedal (only CL) Read throttle pedal (only CR)	Read brake pressure Actuate brake Read wheel velocity
Supervision	Read switches Control indicators Create status	Create status
Calibration	Calibrate	Calibrate
Driver feedback	Calculate feedback Actuate feedback	Not implemented

A summary of all of the subsystems can be found in Table 6.1.

6.2.1 Steering

For the two center nodes, the steering subsystem includes reading the steering wheel angle and calculating the four commanded wheel angles, one for each wheel. This subsystem is completely replicated since the two centre nodes make exactly the same calculations, so even if one of the nodes should fail the system will still work. However, if both of the center nodes are functional, the values of the commanded wheel angles from them will be exactly the same.

Each wheel node then recieves its commanded wheel angle and tries to control the actuator so that the wheel achieves this angle. In addition every wheel node has to check that all of the wheels are turning with respect to each other. The wheel nodes also have the responsibility to read the two sensors that measure the current wheel angle and report this to the rest of the system.

6.2.2 Speed Controlling

In this subsystem the two center nodes read out how the pedals are positioned. These values are then used to control the clutch actuator (for the CL node), the throttle servo (for the CR node) and to calculate brake values for the four wheels. The brake values are calculated in both nodes, but clutch and throttle are only considered in one node each. This design choice was made since if, for example, the CL node should fail, there would be no way of controlling the clutch actuator or read out the clutch pedal value, since these are only connected to this node. This makes the speed controlling subsystem in the centre nodes partially replicated.

The wheel nodes use the brake value calculated by the centre nodes to control the brake actuators. This subsystem also has to read out the speed and brake pressure of each wheel. Currently the speed can only be read from the two rear wheels since there are no speed sensors on the front ones. In addition, the dash board switches are monitored to decide if the parking brake should be applied.

6.2.3 Supervision

The supervision subsystem is responsible for generating a status message for a node. The status is made up from the status of all the subsystems that the node runs and provides a simple way to see if a subsystem has any kind of problem.

In addition this subsystem is responsible for reading the dashboard switches and setting the indicators. This is only done in the center nodes.

6.2.4 Calibration

The wheel nodes need a translation table to be able to match the readings from the wheel angle encoder and the linear sensor measuring the actuator length. It also needs information of the mechanical limits for the wheel. In addition the brake pressure sensor must be calibrated. All these tasks are performed by the calibrating subsystem. The system receives information from the center nodes if it should go into calibration mode and if it should perform any calibration action (such as store left limit, create lookup table, etc.).

Both of the two center nodes read the dash switches to decide if it should switch to calibration mode and generates a message to the wheel nodes. It also has to store its own calibration settings for the steering wheel and the pedals.

6.2.5 Driver feedback

This subsystem, which is only run on the center nodes, controls the MR-brakes that are connected to the steering wheel and the brake pedal. It is supposed to make the driving experience more comfortable and somewhat similar to that of a conventional car.

The possibilites are rather limited since only brakes, which only can produce friction, and not motors, which also can produce torque, are fitted in the car. If these brakes were to be replaced with motors, a lot more advanced feedback could be implemented.

6.3 Tasks and Messages

The subsystems are further divided into distinct tasks which would be easy to implement in software. Each task is then implemented as a single function when programming. The tasks exchange data with each other via messages that can be global or node local.

The tasks and messages are scheduled in a TDMA[1] round. Tasks are run once every second TDMA round and messages have a lifespan of two TDMA rounds. The TDMA round was chosen to 10 ms.

[1]Time Division Multiple Access

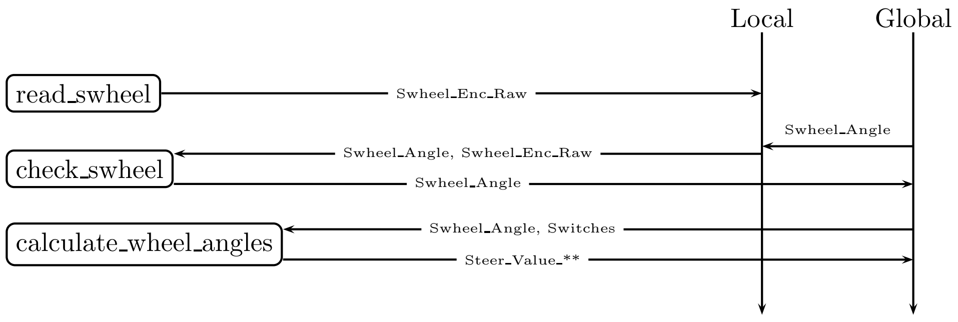


Figure 6.1. The tasks, messages and how they are related for the steering subsystem in the CL node.

In the schedule, each task is allocated a time budget and a deadline. The time budget states how much processor time the task is allowed. Tasks that involve calculations are allowed 200 μs, and other tasks are allowed 100 μs. The deadline specifies when (in the TDMA round) the task execution must be finished.

The time budgets are chosen to "be enough" — no WCET[2] calculations have been made since this is very hard to do analytically [4].

In all the graphs in this section the boxes to the left are the tasks, the horizontal arrows are messages and the two vertical arrows to the right are the local and the global message space. Messages that end in the local message space stay on the node and those that end in the global space are broadcasted on the network.

Whenever a message is ended with "**" below it means that there are actually several copies of this message. One for each wheelnode (replace the "**" with FL, FR, RL or RR) and in some cases additional messages for the center nodes (replace the "**" with CL, CR).

6.3.1 Center nodes

In figures 6.1 and 6.2 the steering subsystem for CL and CR respectively are found. This subsystem is replicated so the graphs are identical.

They start out by reading the steering wheel encoder, and after that this value is compared to the value that the nodes agreed on in the last round to verify that the encoder is working. The agreed value is then broadcasted to the network. This value combined with the state of the dashboard switches (to select different steering modes) is then used to calculate the four commanded wheel angles.

Below is a more in depth description of the tasks and messages involved in the steering subsystem on the center nodes.

[2]Worst Case Execution Time

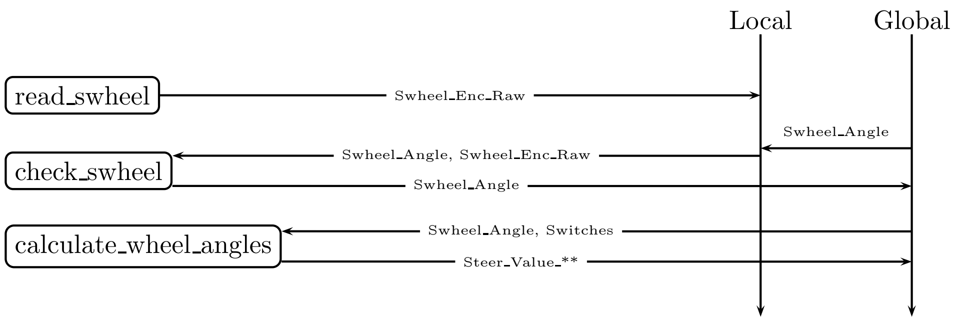


Figure 6.2. The tasks, messages and how they are related for the steering subsystem in the CR node.

Tasks

`read_swheel` Reads out a value from the ten bit steering wheel encoder.

`check_swheel` Checks that the value read by read_swheel is sane.

`calculate_wheel_angles` Produces the commanded wheel angles.

Messages

`Swheel_Enc_Raw` The raw value as read from the 10-bit encoder that is attached to the steering wheel.

`Swheel_Angle` An agreed value representing the steering wheel angle, with negative values when the steering wheel is turned left and positive when it is turned to the right. The message comes replicated from both center nodes.

`Switches` This message is used to select which algorithm the calculate_wheel_angles task should use.

`Steer_Value_**` Commanded wheel angle for a wheel. A negative value means that the wheel should be steered left and a positive that it should be steered right.

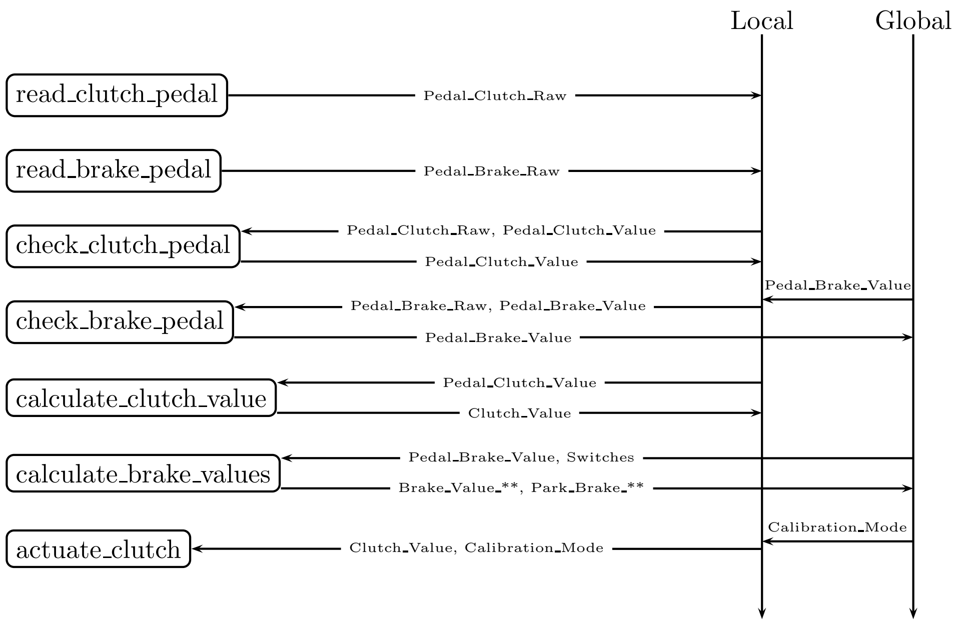


Figure 6.3. The tasks, messages and how they are related for the speed controlling subsystem in the CL node.

The speed controlling subsystem, which can be found in figures 6.3 and 6.4, contains some replicated parts and some that are not.

The replicated part is the brake pedal handling; the tasks read_brake_pedal, check_brake_pedal and calculate_brake_values. This part works just like the steering subsystem; it first reads a raw sensor value, compares this to the old agreed value and agrees on a new value. This agreed value is then used to calculate the commanded brake forces.

The clutch and throttle handling are the un-replicated part of the speed controlling subsystem. They work in a similar fashion to the braking part, except that no agreement is made and no messages are broadcasted.

Below is a short description of all the tasks and messages involved:

Tasks

`read_clutch_pedal` Gets a raw reading of the clutch pedals position (this is only done on the CL node).

`check_clutch_pedal` Verifies that the value from read_clutch_pedal is correct (only on the CL node).

`calculate_clutch_value` Calculates a value suitable for controlling the clutch actuator (only on CL).

`actuate_clutch` Sets PWM value to control the clutch actuator (only CL).

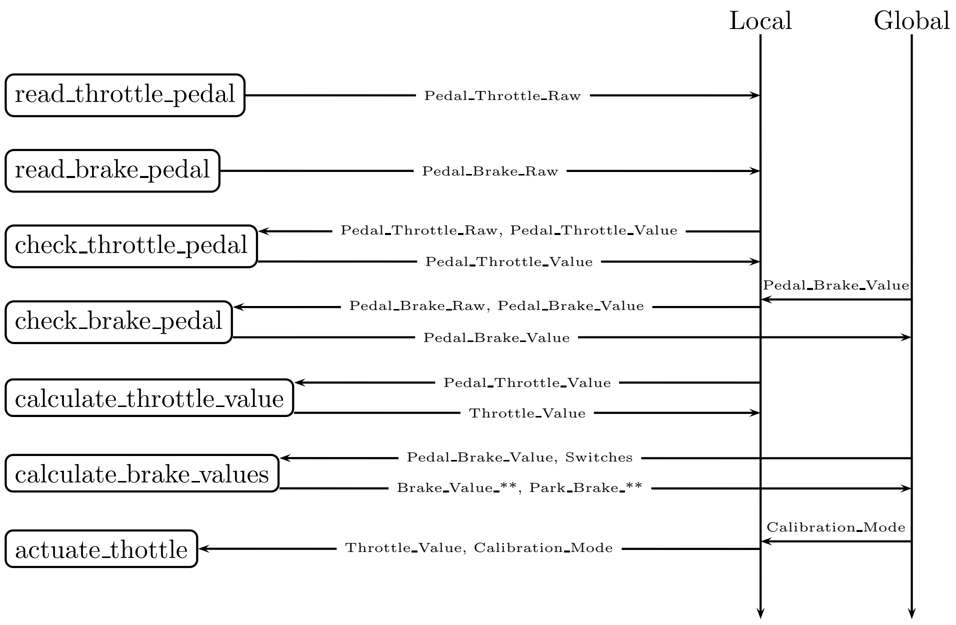


Figure 6.4. The tasks, messages and how they are related for the speed controlling subsystem in the CR node.

`read_throttle_pedal` Gets a raw reading from the throttle pedal (this is only done on the CR node).

`check_throttle_pedal` Sees if the value that read_throttle_pedal reads is sane.

`calculate_throttle_value` Generates a value that can be used to control the throttle servo (only on CR node).

`actuate_throttle` Generates PWM signal from throttle servo (only CR).

`read_brake_pedal` Reads a raw value from the brake pedal. This task is run on both nodes.

`check_brake_pedal` Checks the values from read_brake_pedal to see if they are correct. This task reads values from both nodes and compares them.

`calculate_brake_values` Calculates commanded brake forces for all four wheels.

Messages

`Pedal_Clutch_Raw` Raw value from the clutch pedal.

`Pedal_Throttle_Raw` Raw value from the throttle pedal.

`Pedal_Brake_Raw` Raw value from the brake pedal.

`Pedal_Clutch_Value` Verified value on the clutch pedal.

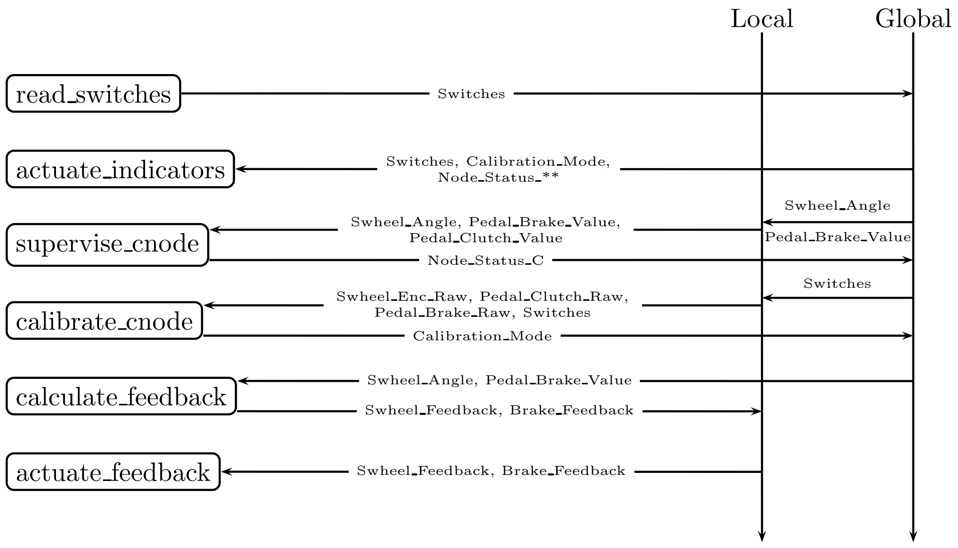

Local
Global
read_switches
Switches
actuate_indicators
Switches, Calibration_Mode, Node_Status_**
Swheel_Angle
supervise_cnode
Swheel_Angle, Pedal_Brake_Value, Pedal_Clutch_Value
Pedal_Brake_Value
Node_Status_C
Switches
calibrate_cnode
Swheel_Enc_Raw, Pedal_Clutch_Raw, Pedal_Brake_Raw, Switches
Calibration_Mode
calculate_feedback
Swheel_Angle, Pedal_Brake_Value
Swheel_Feedback, Brake_Feedback
actuate_feedback
Swheel_Feedback, Brake_Feedback

Figure 6.5. The task, messages and how they are related for the supervising, calibrating and feedback subsystems in the CL node.

`Pedal_Throttle_Value` Verified value on the clutch pedal.

`Pedal_Brake_Value` Agreed value from the brake pedal. This message is produced in both center nodes.

`Clutch_Value` Value that represents the commanded position on the clutch actuator.

`Throttle_Value` Value that is the commanded position on the throttle servo.

`Brake_Value_**` Commanded brake force for wheel FL, FR, RL and RR.

`Park_Brake_**` This message contains a 1 if the park brake on wheel FL, FR, RL or RR should be applied. Otherwise it is 0.

`Calibration_Mode` This is used to prevent the different actuators from moving when the system is in calibration mode.

The supervising, calibrating and feedback subsystems can all be found in figures 6.5 and 6.6.

Supervising is done by checking the status of all messages that are produced by the node. The resulting message is calculated as the sum of the messages from CL and CR. The supervising subsystem also reads out the dashboard switches and controls the indicators to inform and warn the driver.

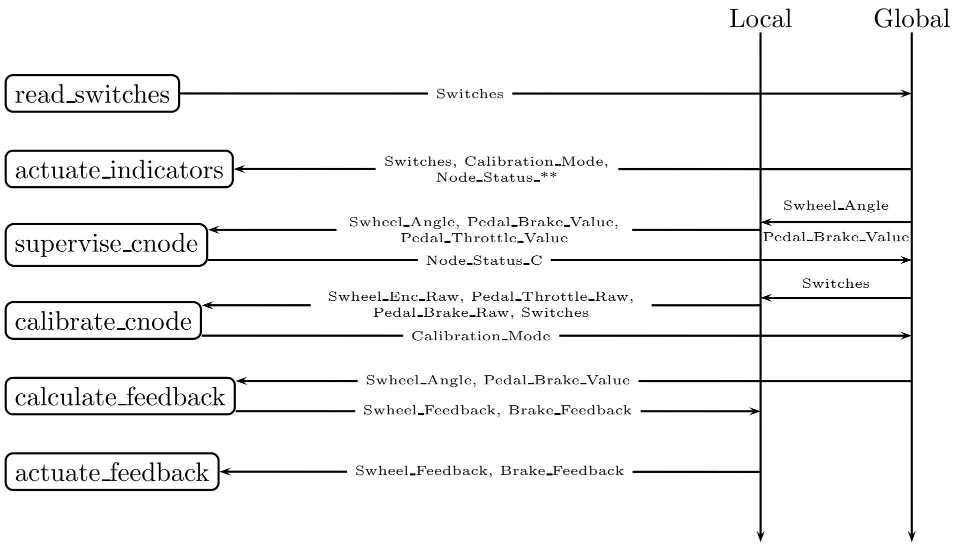

Local
Global
read_switches
Switches
actuate_indicators
Switches, Calibration_Mode, Node_Status_**
Swheel_Angle
Pedal_Brake_Value
supervise_cnode
Swheel_Angle, Pedal_Brake_Value, Pedal_Throttle_Value
Node_Status_C
Switches
calibrate_cnode
Swheel_Enc_Raw, Pedal_Throttle_Raw, Pedal_Brake_Raw, Switches
Calibration_Mode
calculate_feedback
Swheel_Angle, Pedal_Brake_Value
Swheel_Feedback, Brake_Feedback
actuate_feedback
Swheel_Feedback, Brake_Feedback

Figure 6.6. The task, messages and how they are related for the supervising, calibrating and feedback subsystems in the CR node.

The tasks and messages in the supervising subsystem on the center nodes are:

Tasks

`read_switches` Creates a message containing bits for all switches on the dash board.

`actuate_indicators` Controls the various indicators on the dash board.

`supervise_cnode` Checks the total status of the node by analyzing the messages that the other tasks on this node produces.

Messages

`Switches` State of the dashboard switches. Each bit in the message represents one switch; if the switch is on the bit is 1 otherwise the bit is 0.

`Calibration_Mode` This message is used to inform the user if the system is in calibration mode.

`Node_Status_**` The system uses these to inform the driver of any faults in the system.

`Node_Status_C` This message contains the status of the two center nodes. It is created using the status information from the messages Swheel_Angle, Pedal_Clutch_Value, Pedal_Throttle_Value and Pedal_Brake_Value.

Calibration mode is chosen with the dashboard switches, and the procedure is then stepped through by operating another switch. Calibration is made by storing raw sensor readings in the PowerNodes memory. The calibration task on the center nodes must also create the calibration_mode message to inform the other nodes.

Finally the driver_feedback subsystem consists of two tasks and two messages;

Tasks

`calculate_feedback` Calculates values for the feedback by looking on the steering wheel angle and the brake pedal value.

`actuate_feedback` Uses the value calculated by calculate_feedback to control the magneto reological brakes that are fitted to the steering wheel and the brake pedal.

Messages

`Swheel_Feedback` The amount of feedback that should be applied to the steering wheel. It is created using the Swheel_Angle message.

`Brake_Feedback` Amount of feedback that should be applied to the brake pedal, created using the Pedal_Brake_Value message.

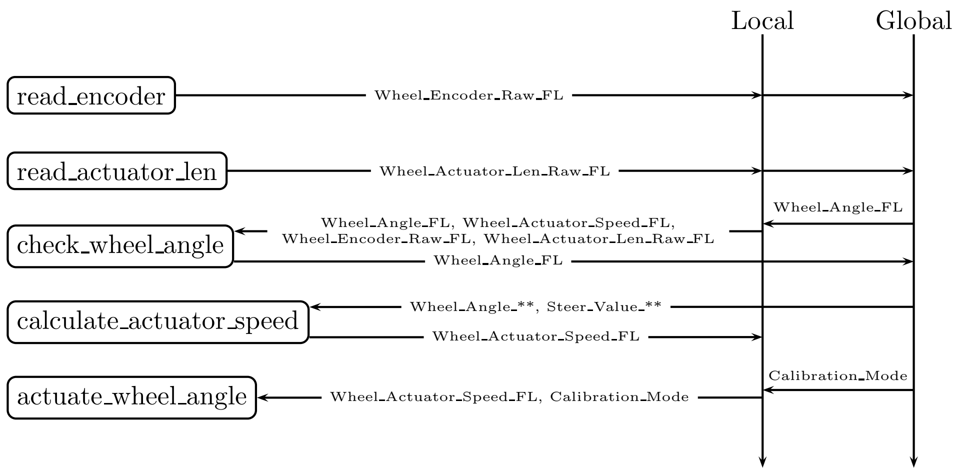


Figure 6.7. The tasks, messages and how they are related for the steering subsystem in the front left wheel node.

6.3.2 Wheel nodes

All of the four wheel nodes run the same tasks, but they produce different messages. For example; the front right node produces a message called Wheel_Angle_FL while the front right node produces Wheel_Angle_FR.

Figures 6.7, 6.8, 6.9 and 6.10 list the tasks and messages for the steering subsystem.

This subsystem starts out by reading the raw sensor values that measure the wheel angle. These two values are also broadcasted for debugging purposes. After that the values are checked by comparing them to each other and a predictor, the check_wheel_angle task is also responsible for updating that predictor. The final checked value of the wheel angle is then broadcasted.

In the task calculate_actuator_speed *all* of the current and commanded wheel angles are used to calculate how the steer actuator should be controlled. This is where the wheel angle controller (see Section 4.2) is implemented. The last task's purpose is simply to generate the PWM signal for controlling the motor control box.

The tasks and messages in the steering subsystem on the wheel nodes are described below.

Tasks

`read_encoder` Reads a raw value from the fourteen bit digital encoder that measures the wheel angle.

`read_actuator_len` Reads out a raw value from the linear potentiometer that measures the length of the steer actuator.

`check_wheel_angle` Compares the value produced by read_encoder and the value from read_actuator_len to a predicted value of the wheels angle.

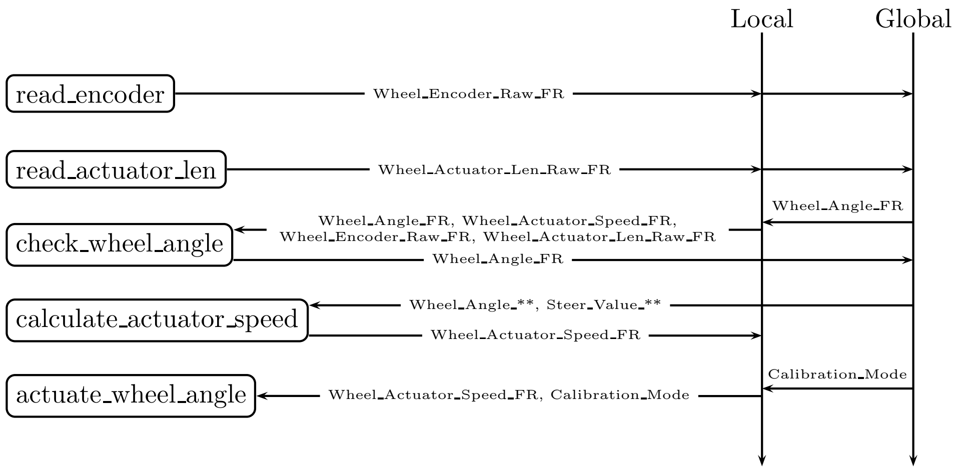


Figure 6.8. The tasks, messages and how they are related for the steering subsystem in the front right wheel node.

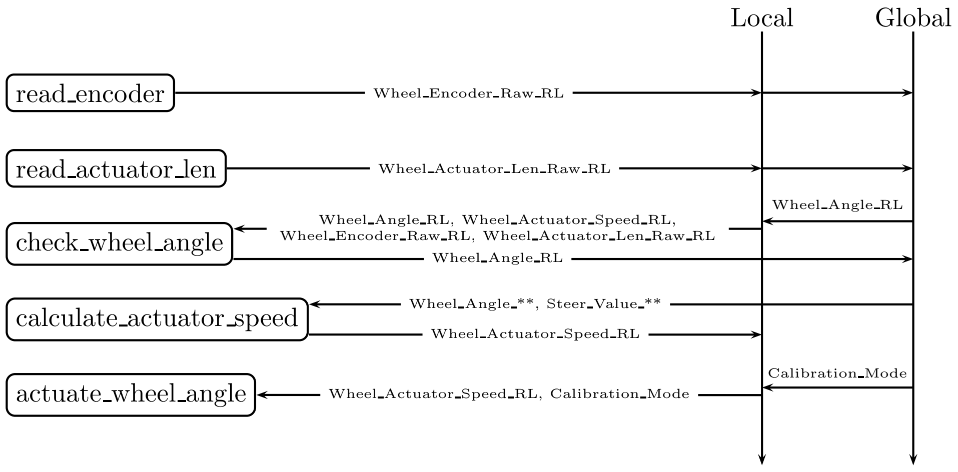


Figure 6.9. The tasks, messages and how they are related for the steering subsystem in the rear left wheel node.

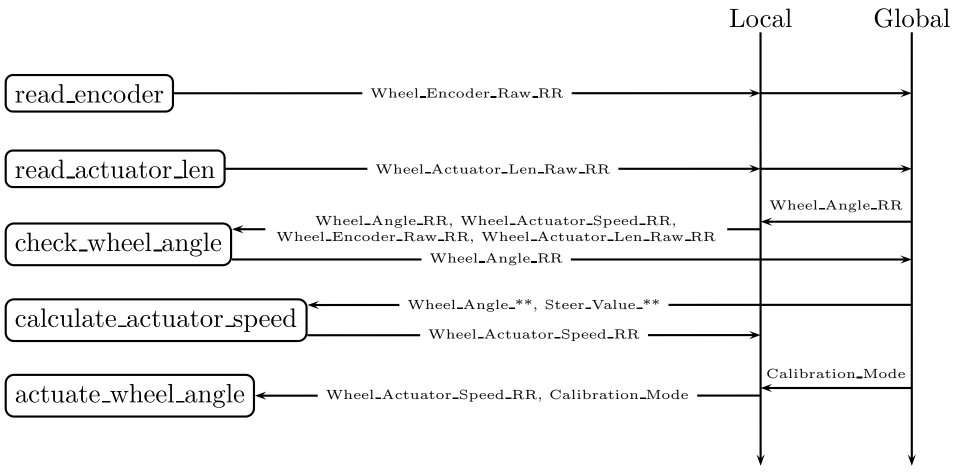


Figure 6.10. The tasks, messages and how they are related for the steering subsystem in the rear right wheel node.

`calculate_actuator_speed` Calculates the value that should be sent to the motor control box by comparing the commanded wheel angle and the current wheel angle for all four wheels.

`actuate_wheel_angle` Sets a PWM value to control the wheel angle actuator.

Messages

`Wheel_Encoder_Raw_**` Raw value from the encoder attached to the wheel.

`Wheel_Actuator_Len_Raw_**` Raw value representing the length of the steer angle actuator as measured by the linear sensor.

`Wheel_Angle_**` Verified value representing the angle of a wheel. This value is adjusted so negative values mean that the wheel is steered to the left and positive that it is steered to the right.

`Steer_Value_**` Commanded angle for a wheel with negative values representing that the wheel should be steered to the left and positive values for right.

`Wheel_Actuator_Speed_**` The value that should be sent to the motor control box. A negative value mean that the wheel should be turned left and a positive that it should be turned right.

`Calibration_Mode` This is used to prevent the actuator from moving when the system is in calibration mode.

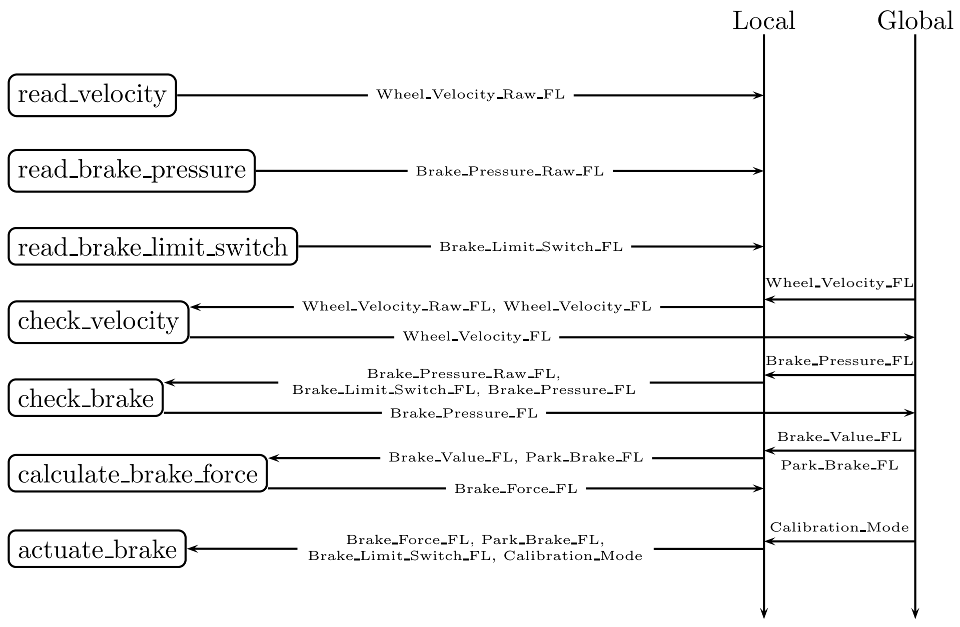


Figure 6.11. The tasks, messages and how they are related for the speed controlling subsystem in the front left wheel node.

In figures 6.11, 6.12, 6.13 and 6.14 the speed controlling subsystem is specified.

It begins by reading the speed sensor and the brake sensors. After that, those values are checked and the validated messages are broadcasted. The second part controls the brake motor by first calculating a control value and then using this value to generate the PWM signal.

The speed controlling subsystem in the wheel nodes use the tasks and messages that are described below.

Tasks

`read_velocity` Reads the speed sensor for this wheel.

`check_velocity` Checks the value produced by read_velocity.

`read_brake_pressure` Reads the brake pressure sensor.

`read_brake_limit_switch` Reads the limit switch in the brake unit.

`check_brake` Checks that the brake works by comparing the old value with the new one and the limit switch reading.

`calculate_brake_force` Calculates the value that should be sent to the brake motor control box. This task also calculates if the park brake lock should be applied.

`actuate_brake` Sets PWM value to control the brake motor and the park brake lock.

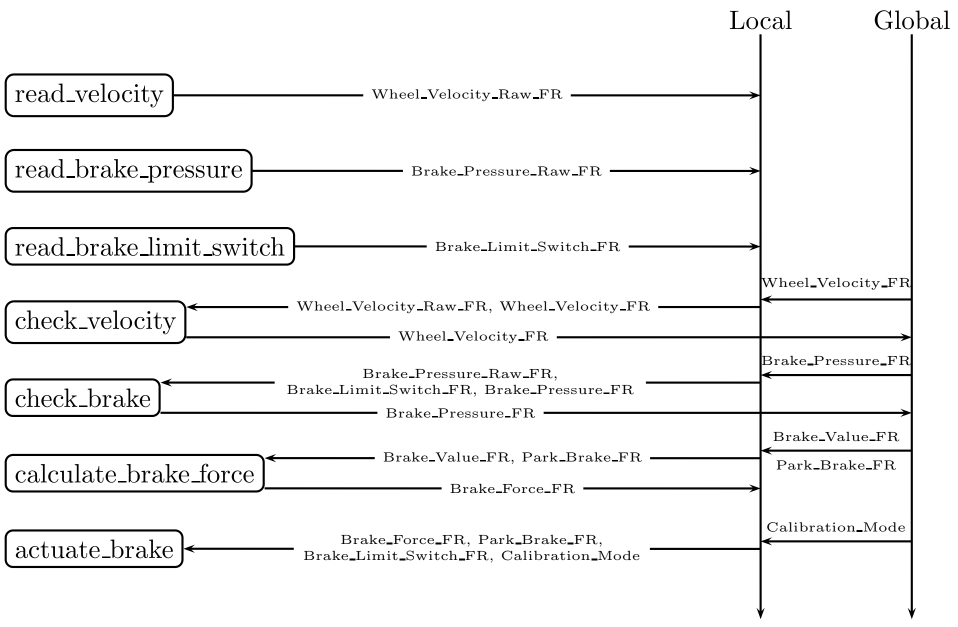


Figure 6.12. The tasks, messages and how they are related for the speed controlling subsystem in the front right wheel node.

Messages

`Wheel_Velocity_Raw_**` Raw value representing the period of the signal coming from the speed sensor.

`Brake_Pressure_Raw_**` Raw value from the brake pressure sensor.

`Brake_Limit_Switch_**` State of the piston in the brake actuator. If this message contains a 1 the piston is at its rear limit.

`Wheel_Velocity_**` Verified value on the velocity of a wheel.

`Brake_Pressure_**` Verified value on the brake pressure.

`Brake_Force_**` The value that should be sent to the brake motor control box. It is built up using the commanded brake value and whether the park brake should be activated.

`Calibration_Mode` This value is used to stop the brake actuator from moving when the system is in calibration mode.

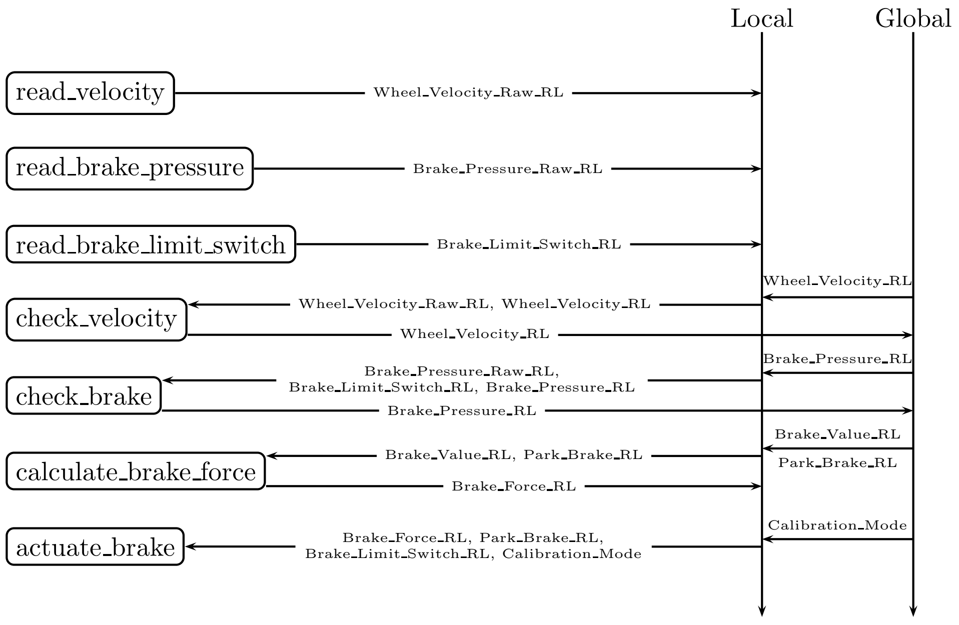


Figure 6.13. The tasks, messages and how they are related for the speed controlling subsystem in the rear left wheel node.

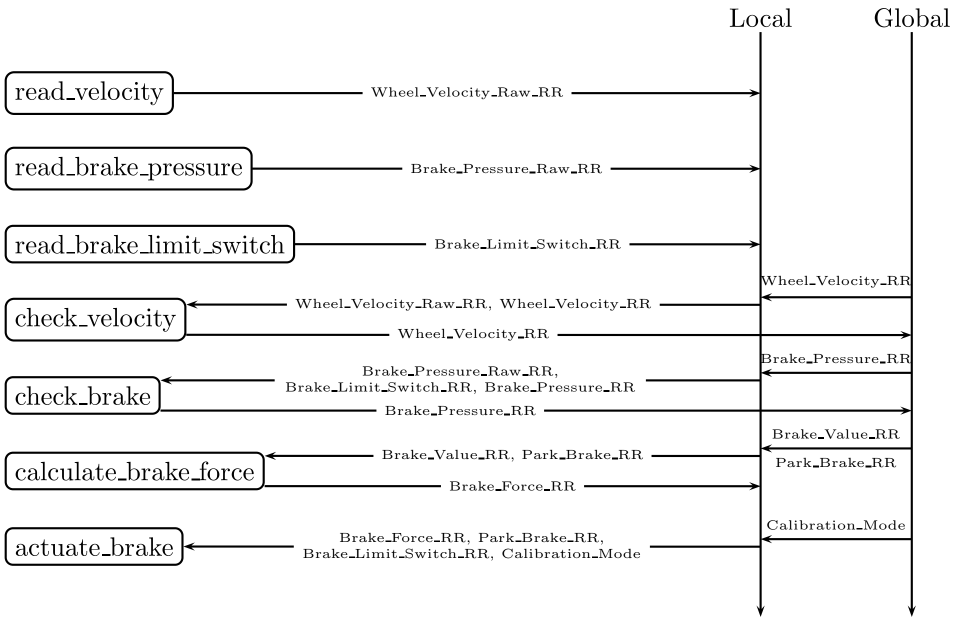


Figure 6.14. The tasks, messages and how they are related for the speed controlling subsystem in the rear right wheel node.

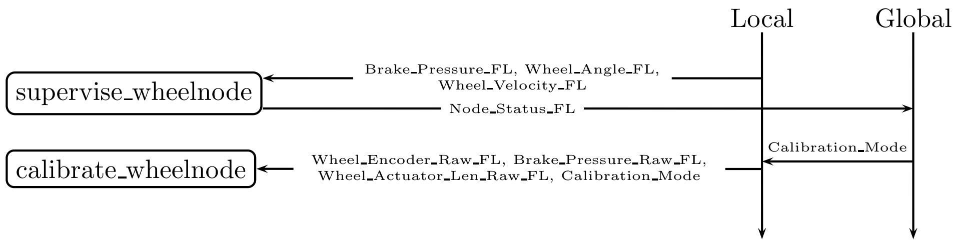

Local
Global
supervise_wheelnode
Brake_Pressure_FL, Wheel_Angle_FL, Wheel_Velocity_FL
Node_Status_FL
calibrate_wheelnode
Calibration_Mode
Wheel_Encoder_Raw_FL, Brake_Pressure_Raw_FL, Wheel_Actuator_Len_Raw_FL, Calibration_Mode

Figure 6.15. The task, messages and how they are related for the supervising and calibrating subsystems in the front left wheel node.

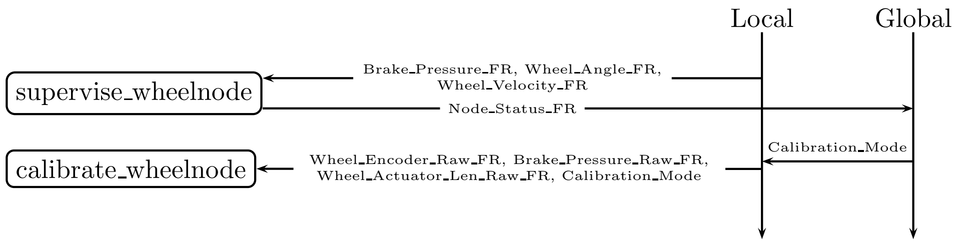

Local
Global
supervise_wheelnode
Brake_Pressure_FR, Wheel_Angle_FR, Wheel_Velocity_FR
Node_Status_FR
calibrate_wheelnode
Calibration_Mode
Wheel_Encoder_Raw_FR, Brake_Pressure_Raw_FR, Wheel_Actuator_Len_Raw_FR, Calibration_Mode

Figure 6.16. The task, messages and how they are related for the supervising and calibrating subsystems in the front right wheel node.

The last two subsystems, calibrating and supervising, are described in figures 6.15, 6.16, 6.17 and 6.18. They each contain a single task;

Tasks

`supervise_wheelnode` Checks the nodes status by analyzing messages that this node produces.

`calibrate_wheelnode` Listens for calibration commands that are sent out by the center nodes and takes appropriate action (one of; store limit, create a table that translates between actuator lengths and wheel angles, store zero angle and store calibration values for the brake pressure sensor).

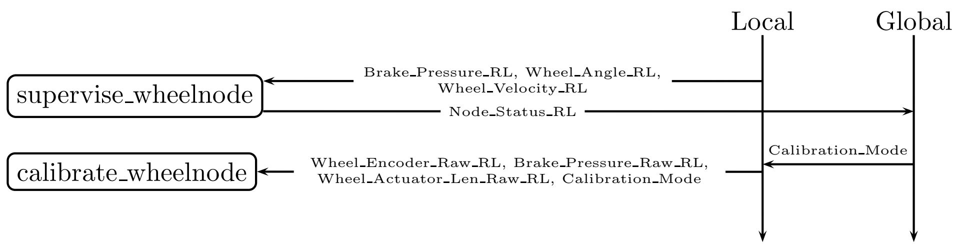

Local
Global
supervise_wheelnode
Brake_Pressure_RL, Wheel_Angle_RL, Wheel_Velocity_RL
Node_Status_RL
Calibration_Mode
calibrate_wheelnode
Wheel_Encoder_Raw_RL, Brake_Pressure_Raw_RL, Wheel_Actuator_Len_Raw_RL, Calibration_Mode

Figure 6.17. The task, messages and how they are related for the supervising and calibrating subsystems in the rear left wheel node.

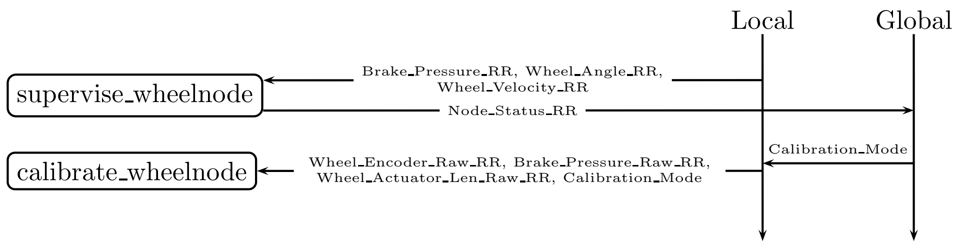

Local
Global
supervise_wheelnode
Brake_Pressure_RR, Wheel_Angle_RR, Wheel_Velocity_RR
Node_Status_RR
Calibration_Mode
calibrate_wheelnode
Wheel_Encoder_Raw_RR, Brake_Pressure_Raw_RR, Wheel_Actuator_Len_Raw_RR, Calibration_Mode

Figure 6.18. The task, messages and how they are related for the supervising and calibrating subsystems in the front left wheel node.

Chapter 7

Results

This chapter answers the question on how well the theoretical controllers and algorithms presented in Chapter 4 and 5 work when implemented in the car.

It starts out by discussing the wheel angle controller, and thereafter the brake controller is evaluated. Something is also said about the algorithms that distribute brake forces and steer angles among the wheels. Only simple tests were performed on the system, since the time frame did not allow more thorough evaluations.

7.1 Wheel Angle Controller

As a start, the wheel angle controller was implemented in one of the rear nodes, exactly as the simulated one (see Section 5.1), with the same parameters on PI part of the controller. A first test showed, however, that these parameters could not be used at all, since the gain of the model did not correspond to the real system — in the model the loop was closed with the DC motor angle as the measured signal, and in the real system the wheel angle is used.

To adapt the PI-controller parameters, the Ziegeler-Nichols method was used on the real system this time, giving $K_0 = 10$ and $T_I = 0.23\,\mathrm{s}$. The corresponding parameters for the controller were:

$$\mathrm{PI} \quad : \quad K = 0.45 \cdot K_0 = 4.5,\ T_I = \frac{T_0}{1.2} = 0.19$$

A second test was performed with a step reference, and the results showed a significant overshoot when the PI-controller was in action — a well known phenomena when using the Ziegeler-Nichols method. To reduce that, the parameters were adjusted a couple of times, resulting in the following values:

$$K = 2, T_I = 1\,\mathrm{s}$$

The switching between Bang-Bang and PI controller was set fixed at 1.75°. At this angle error the Bang-Bang and PI controller give the same control signal in the wheel with the largest angle error (i.e. the wheel that moves with the maximum speed). This makes the transition between the two controllers smooth if the control signal is close to the maximum value.

Next, the second rear node was programmed with the same controller, in order to verify the coordination between the wheels when the bang-bang controller was in action. In the test, two different step references were used in nodes, one going form -1000 to 1000 increments[1] and the other from 0 to 1000. The two signals were initiated at the same time, and the wheels were unloaded during the test.

The result, seen in Figure 7.1, was satisfactory, and agrees quite well with the simulated one in Figure 5.6. The wheel with the largest error was running at maximum speed the whole time, while the other had adapted its speed, so both wheels reached their destination at the same time.

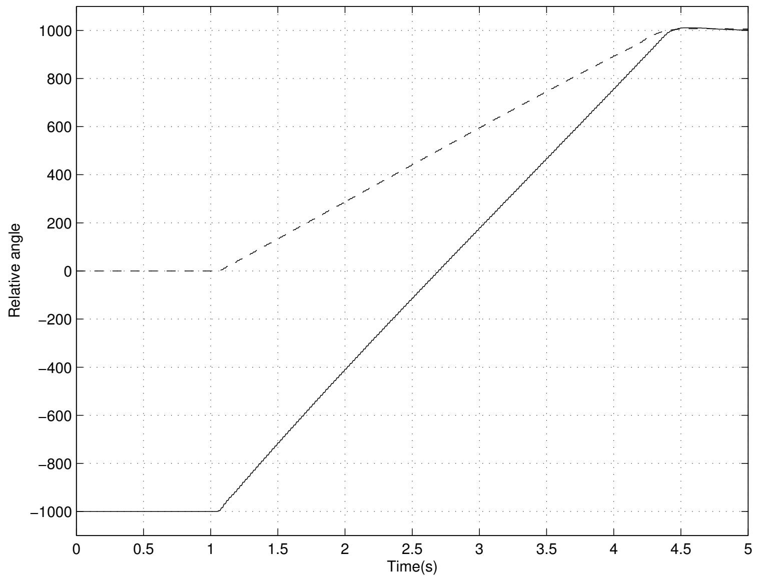


Figure 7.1. Step responses for the rear wheels with different reference values.

To further test the bang-bang controller, tire friction was added to one of the wheels. The test was very simple — the wheel with the largest error was prevented from turning by trying to hold the tire by hand in a firm grip. Although this is an unscientific testing procedure, it gave a quantitative understanding about the behavior of the controller.

The result, seen in Figure 7.2, shows that the controller indeed could adapt to the change in conditions, and confirm the simulated results in Figure 5.7. The wheel with the lesser error started to slow down when it came closer to the reference value, since the other wheel angle error did not diminish as fast as expected. Due to the shifting to the PI-controller, the time when the references were reached

[1]One increment is $\frac{360}{2^{14}}$ degrees.

differ a little. A small notch can also be seen in the graph when the controllers where switched. This notch could be removed by implementing a more advanced algoritm which decides when the controller switching should be made.

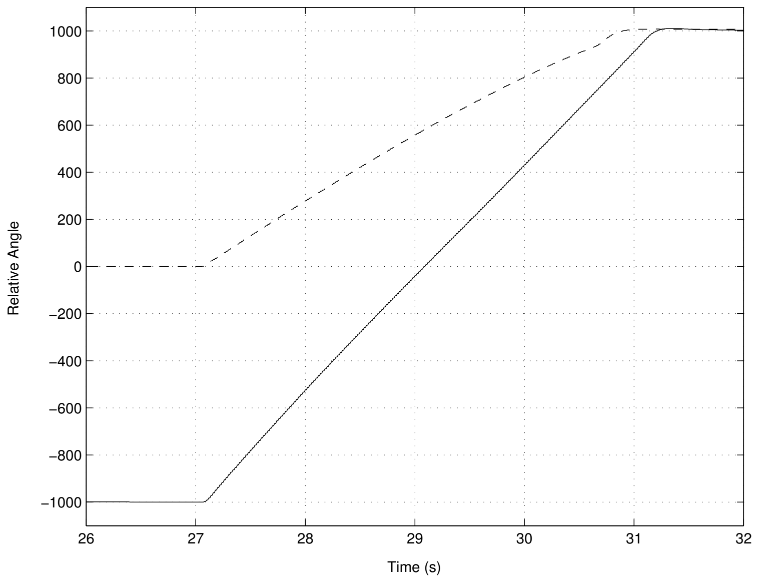


Figure 7.2. Step responses with tire friction simulation for the rear wheels.

The car was elevated so the wheels were not in contact with the ground during all of the tests described above.

The tests above show that the wheel moves 40° in around 3.5 s. This limit is due to the top speed of the motors and the gear ratio of the ball screws. In a panic situation, tests have shown that the driver can turn the steering wheel up to 800°/s, which corresponds to 80°/s at the wheels. This is more then four times faster then the maximum speed possible with the actuators fitted in this car, and the only way to remedy this is to replace the actuators with faster ones.

7.2 Brake Controller

Only an open loop brake controller was implemented, due to the limited time frame. However, some simple tests were performed to verify the impact of some of the drawbacks, discussed in Section 5.3, with a controller of this type.

The controller structure was made very simple. The PWM-signal to the actuator was made directly proportional to the brake pedal position, i.e. full pedal reading represented 100% PWM duty cycle. Only when the pedal was released completely, the brake piston was explicitly retracted.

In Figure 7.3 the results of two simple tests are seen. First, the pedal was pressed as fast, and as far, as possible and then released. The result shows a delay of almost a second before the pressure was built up in the system. Also, which is more serious, the pressure did not decrease until the pedal was released fully.

Second, the parking brake switch was turned on, which sets the PWM duty cycle to 100% instantly, representing a step input. The result confirms the first result stated above, i.e. the delay in the system before full brake pressure was reached.

Both tests point to the fact that the open loop controller is not suitable for the brake actuators installed in the car.

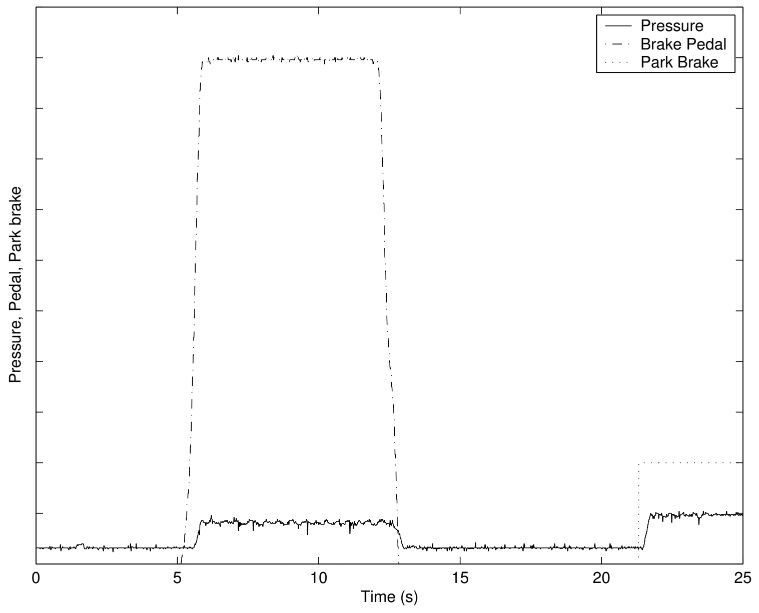


Figure 7.3. Two simple tests performed on the open loop brake controller.

7.3 Algorithms

The steer and brake distribution algorithms have not been implemented or tested due to lack of time. The car can not be driven on normal roads since it is not licensed, and to evaluate the algorithms, the car has to be driven with different speeds. Safety is also an important factor since the authors insurance would probably not be valid if an accident happened while test driving the car.

Chapter 8

Summary and Conclusions

This project has shown that the Sirius 2001 Concept Car is an ideal platform for research in safety, redundant sensor handling and vehicle dynamics just to name a few. Even though the car still have a couple of technical flaws that somewhat limit its capabilities, the freedom of the application programmer is enormous. The flaws are also described in this report, so they can be modelled easily.

The software and scheduling that are implemented in the car make it especially easy to target one area and concentrate on that without the need to learn other aspects of the system. This report is also useful when starting new projects using the car.

However, the main objective of the project (stated in Section 1.2) has not been reached, as the car is, at this time, not fully functional. Above all, this is due to lack of time during the implementation and testing phase. This is a direct consequence of the numerous problems encountered throughout the whole project, like malfunctioning hardware and problems with the software tool licensing to name a few. Despite this, all of the goals stated in Section 1.2 has, fully or partly, been reached;

- *The different parts included in the control system should be identified and well documented.* — A complete listing of the hardware is found in Chapter 2. Chapter 6, as well as Appendix A, includes a comprehensive guide on how to master the realtime controller network.

- *The implemented controllers and algorithms should be modified so the car behaves in a consistent manner when driven.* — A wheel angle controller has been implemented with satisfying results (Section 7.1) and drawbacks with an open loop brake controller has also been verified. However, the brake controller should have been modified to fulfill the demand of consistent behavior of the car. Also, algoritms for generating reference values for the controllers (discussed in Section 5.2 and 5.4) has not been implemented at all.

- *The system should be able to handle redundant components in order to* *detect faults.* — Section 4.4 and 4.5 includes a discussion on this topic, but as with the algorithms above, it has not been implemented in software.

8.1 Future work

There are still areas of the car that could be improved further. This section will list some of these.

8.1.1 Hardware Modifications

Brake Actuators The manual parking brake makes the rear brakes stick since brake fluid is drawn through the non-return valve which prevents the brake fluid from going out through the fluid container.

There are two solutions to this problem, one simple and one requiring a lot more effort. The simple one is to make the actuators resemble an ordinary brake systems, i.e. drill a new hole for the brake fluid container positioned in such a way that the piston blocks it right before pressure is built up in the system, but makes the container and the system in contact with each other when the piston is retracted.

The speed of the brake actuator can also be questioned. A solution which would work better with regard to this is to have a constant pressure container with a valve regulating the pressure to the brake caliper.

The solution requiring more effort involves a complete redesign of the brake actuator and is suitable for a Master Thesis project by its own.

Dashboard The driver interface is limited to LED:s and simple switches. A display would be more appropriate to let the driver know what is going on with the car.

Electronics The adaptive electronics for the two center nodes need a remake. And all of the boards should be redesigned to better protect the PowerNodes (i.e. use opto couplers and other protective electronics).

Sensors A yaw rate sensor would be needed to implement more advanced algorithms. Such a sensor could be connected to one of the PowerNodes via the CAN interface. This would make it possible to use a standard yaw rate sensor form any modern car.

Power supply The charging of the batteries is not optimal. One solution is to convert the whole car to use the 24V power supply system, another is to convert it to the new 42V system that is believed to be fitted in the cars of tomorrow.

Stress calculations The critical parts like the universal joints should be tested.

8.1.2 Software Modifications

Algorithms More advanced algorithms for both steering and braking could be implemented. Both ones that make more use of the existing sensors in the car and those that would require fitting of additional sensors.

Controllers The implemented controllers need further testing, and they can probably be improved in many areas. One is to derive an algoritm that dynamically set the value for switching between the two steer angle controllers.

Redundant sensors More advanced algorithms to decide if a sensor is failing. The algorithms could probably also be refined to deliver safe values even if fail situations.

Failsafe software The car should be able to adjust its capabilities and handling to cope with certain faults in the system, so called degraded operation modes.

Safety The car needs a lot of testing to verify the systems and the implemented software. It is also possible to implement crash avoidance, ABS and various anti skid systems.

Bibliography

[1] BEI Technologies Inc, `http://www.beiduncan.com/`. *Model 610*. Filename[1]: [BEIDuncan 610 linjär givare.pdf].

[2] BEI Technologies Inc, `http://www.beiduncan.com/`. *Throttle position and industrial control sensor modules*. Filname[1]: [9811.9812.pdf].

[3] BOSCH, `http://www.bosch.com/`. *Pressure Sensor*. Filname[1]: [pressure_sensor.jpg].

[4] Burns, A and Wellings, A. *Real-time systems and programming languages : Ada 95, real-time Java and real-time Posix*. Addison-Wesley, 75 Arlington Street, Suite 300, Boston MA 02116, USA, 2001.

[5] T Glad and L Ljung. *Reglerteknik. Grundläggande teori*. Studentlitteratur, 2nd edition, 1989. In Swedish.

[6] T Glad and L Ljung. *Reglerteori. Flervariabla och olinjära metoder*. Studentlitteratur, 1997. In Swedish.

[7] Fredrik Gustafsson. *Adaptive Filering and Change Detection*. Wiley, 2000.

[8] HENGSTLER, `http://www.hengstler.de/index_e.html`. *Absolute Shaft Encoders*. Filename[1]: [A-DGpage106-182fileD.pdf].

[9] HENGSTLER, `http://www.hengstler.de/index_e.html`. *Installation instructions*. Filename[1]: [ra58-s.pdf].

[10] HEWLETT PACKARD, `http://www.elfa.se/`. *Low Input Current Logic Gate*. Filename[1]: [HCPL2200.pdf].

[11] HiTEC RCD USA Inc, `http://www.hitecrcd.com/`. *ANNOUNCED SPECIFICATION OF HS-805BB+ MEGA 1/4 SCALE SERVO*. Filename[1]: [hs805.pdf].

[12] HiTEC RCD USA Inc, `http://www.hitecrcd.com/`. *General Servo Information*. Filename[1]: [Servomanual.pdf].

[13] Dan Holt. Brake by-wire. *Service Tech Magazine*, pages 18 – 20, January 2002.

[14] J. Bolin and J. Hedberg. Implementation of a Distributed Control Application Based on the TTT/C Architecture. Master's thesis, Department of Computer Engineering, Chalmers University of Technology, Göteborg, Sweden, March 1999.

[15] J. Sridhar and H. Hatwal. A Comparative Study of Four Wheel Steering Models Using the Inverse Solution. *Vehicle System Dynamics*, (21):1–18, 1992. Department of Mechanical Engineering, Indian Institute of Technology, Kanpur.

[16] Leine & Linde, `http://www.leinelinde.se/`. *Mounting instructions*. Filename[1]: [mount-manual_synchro-flange.pdf].

[17] Leine & Linde, `http://www.leinelinde.se/`. *PARALLEL 670/671*. Filename[1]: [670,671parallel_db_eng.pdf].

[18] LORD Corporation/Rheonetic, `http://www.lord.com/`, `http://www.rheonetic.com/`. *M.R. BRAKE ASSEMBLY*. Filename[1]: [MRB2107-3WEB.pdf].

[19] LORD Corporation/Rheonetic, `http://www.lord.com/`, `http://www.rheonetic.com/`. *MR DRUM BRAKE ASSY*. Filename[1]: [reo.broms_RD-2028-18X.jpg].

[20] LORD Corporation/Rheonetic, `http://www.lord.com/`, `http://www.rheonetic.com/`. *MRB-2107-3 Product Bulletin*. Filename[1]: [MRB_2107_3_2002_20_0.pdf].

[21] LORD Corporation/Rheonetic, `http://www.lord.com/`, `http://www.rheonetic.com/`. *Rheonetic Wonder Box Device Controller Kit*. Filename[1]: [RD_3002_03_46_0.pdf].

[22] M. Bruce. Distribuerad Brake-By-Wire based on TTP/C. Master's thesis, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden, May 2002.

[23] maxon gear, `http://www.maxonmotor.ch/index_a.cfm`. *maxon gear Planetary Gearhead GP 32 A*. Filename[1]: [GP32 A_110367.pdf].

[24] maxon motor, `http://www.maxonmotor.ch/index_a.cfm`. *maxon DC motor RE 35*. Filename[1]: [RE35_118777.pdf].

[25] maxon motor, `http://www.maxonmotor.ch/index_a.cfm`. *maxon DC motor RE 40*. Filename[1]: [RE40_148867.pdf].

[26] maxon motor, `http://www.maxonmotor.ch/index_a.cfm`. *maxon motor control 4-Q-DC Servoamplifier ADS 50/5*. Filename[1]: [ADS 50-5_145391.pdf].

[27] maxon motor, `http://www.maxonmotor.ch/index_a.cfm`. *maxon motor control ADS 50/10*. Filename[1]: [ADS 50-10_201583.pdf].

[28] maxon motor, `http://www.maxonmotor.ch/index_a.cfm`. *maxon motor control Choke on plug-in Card*. Filename[1]: [choke-133350.pdf].

[29] maxon tacho, `http://www.maxonmotor.ch/index_a.cfm`. *Digital Encoder HEDL 55__ with Line Driver RS 422*. Filename[1]: [HEDL-5540_110514.pdf].

[30] Motorola, Inc., `http://www.motorola.com/`. *MPC555/556 User's Manual*. Filename[1]: [START.pdf].

[31] Nielsen, L and Eriksson, L. *Course material Vehicular Systems*. Bokakademin Linköping, Linköpings universitet, Sweden, 2002.

[32] Östergrens Elmotor AB, `http://www.ostergrens.se/`. *Elektriska bromsar, FSB-serien*. Filename[1]: [Elbroms-FSB003.htm].

[33] P. Björklund and P. Drougge. Distribuerad Brake-By-Wire - demonstrator baserad på TTP/C-kommunikation. Master's thesis, Department of Computer Engineering, Chalmers University of Technology, Göteborg, Sweden, January 2000.

[34] Saia-Burgess, `http://www.saia-burgess.com/`. *Switches*. Filename[1]: [Microswitches.pdf].

[35] Sirius Project group 2001. Sirius 2001 Brake Sytem and Wheel Suspension, May 2001. This reoprt contains a more detailed description of the modified brake system and wheel suspension.

[36] Sirius Project group 2001. Sirius 2001 Main Report, May 2001. This report is a summary of the five parts of the project.

[37] SKF Linear Motion, `http://www.skf.se/`. *CAPR 43*. Filename[1]: [kulskruv CAPR 43Ax100x2A1G3F.pdf].

[38] SKF Linear Motion, `http://www.skf.se/`. *CARR Linear Actuators*. Filename[1]: [kulskruv CARN 32x200x4.pdf].

[39] SKF Linear Motion, `http://www.skf.se/`. *Control unit CAED ANR*. Filename[1]: [motorkontroller CAED-ANR.bmp].

[40] Henrik Thare. Säkerhetskritiska realtidssystem, 1999. Mälardalen Real-Time Research Center.

[41] TTTech Computertechnik AG, `http://www.tttech.com/`. *A TTP Development Board for the Time-Triggered Architecture*, 1.3.00 edition, December 2000. Filename[1]: [TTPPowerNodeV1_3.pdf].

[42] TTTech Computertechnik AG, `http://www.tttech.com/`. *The Cluste Design Tool for the Time-Triggered Protocol TTP/C*, 3.2 edition, July 2002. Filename[1]: [TTP_Plan_user_man3.2.pdf].

[43] TTTech Computertechnik AG, `http://www.tttech.com/`. *The Download Tool for the Time-Triggered Protocol TTP/C*, 4.4.0 edition, July 2002. Filename[1]: [TTP_Load_user_man4.4.0.pdf].

[44] TTTech Computertechnik AG, `http://www.tttech.com/`. *The Node Design Tool for the Time-Triggered Protocol TTP/C*, 3.2 edition, July 2002. Filename[1]: [TTP_Build_user_man3.2.pdf].

[1]Available on the included CD-ROM.

Appendix A

Programming and Software Tool User guide

In the following chapter some fundamental issues about the design behind TTTech's products are discussed as well a short introduction on how to program the cluster using TTTech's software products, TTPtools. Some reflections on scheduling can also be found in this chapter.

A.1 The cluster

The cluster consists of two or more nodes connected to each other by a communications bus or star. Each node in the system has one CPU for the host application and another for the communications system. The nodes in the cluster considered in this master thesis are six TTTech PowerNodes. The host CPU is Motorola MPC-555 and the communications processor is TTTech's own TTPC-C1 chip.

The host CPU is where all the computations are made and the communications system is responsible for all data exchange between the nodes. The interface between these are called the CNI, or Communication Network Interface.

A.1.1 Communications Subsystem

Communication between the nodes happen on a broadcast type bus or star topology network using the time-triggered protocol TTP/C. Broadcast type means that a message will not have a receiver, but instead all nodes can read it. The difference between bus and star topology is that in a star network each node is connected to some sort of hub, whereas in a bus topology a single bus connects the nodes together.

Since the communications are time-triggered, all messages must be defined in advance, both in the temporal and the value domain[1]. This also guarantees that the nodes all have one synchronized clock and it makes it easy to detect errors.

[1] *When* the message is sent and *what* it contains.

To access the network the nodes follow Time Division Multiple Access, or TDMA, rounds. This means that a node is only allowed to transmit in its own slot in the TDMA round. For this to work there must be some kind of scheme which all the nodes can access which defines the TDMA round and the messages sent. This scheme is called the MEssage Descriptor List, MEDL. The MEDL is stored within each node and must be consistent on all nodes in the cluster.

To create the MEDL TTTech has supplied a tool called TTPplan. This tool aids in the creation and definition of a cluster. The user defines the nodes in the cluster and which subsystems they should run. In addition, messages that subsystems produce are defined in the temporal (that is; when) and the value (that means; type and size). Using this information TTPplan can produce a communications scheme which in turn is the basis for the MEDL. TTPplan also includes utilities to view and modify the schedule graphically, which significantly simplifies the task.

A.1.2 Host Subsystem

Each node in the cluster runs TTTech's own proprietary operating system, TTPos. The OS hides some of the complexity involved in communicating with other nodes and handles the scheduling for tasks that run on the host processor.

The schedule for a node consists of rules when a task is run and information about how much CPU-time it is allowed. This schedule is made with another tool from TTTech, namely TTPbuild.

TTPbuild takes a cluster database, created by TTPplan, as input and lets the user define individual tasks for the subsystems on a node.

A.2 Using the TTPtools

There are essentially three steps involved when creating a TTP-cluster;

1. Planning
2. Scheduling
3. Application programming

After that, the finished schedule and application data must be transferred to the hardware to make a working system.

This is just an overview and a short introduction to the steps involved when creating a TTP cluster. Please refer to the manuals [42, 44, 43] supplied with the tools for further reference.

A.2.1 Planning

The planning is probably the most important, and definitely the most time-consuming step when defining a TTP cluster. Since the complete system is defined beforehand, it is very important that this step is well thought through before continuing to the next.

This step should result in a complete description of the system. This includes the different subsystems (this can be seen as a logical group of functions, for example seeing or hearing) and all the tasks in the subsystems (a task is a single function, for example read a sensor or calculate a value). In addition to this there should be a complete description of the messages that have to be exchanged between the tasks.

The result after this step should be somewhat similar to that in Chapter 6. All subsystems, tasks, messages and how they interact must be clearly defined.

A.2.2 Scheduling

If the details from the planning stage are thoroughly written down this step is as easy as "fill in the empty fields".

The work is exclusively done in TTPtools. First TTPplan is used to define the cluster schedule and after that TTPbuild is used to define the schedule on the node level.

In TTPplan, the properties of the cluster and the nodes are specified. Also, all global messages and all subsystems are specified here. After that, it is time to use TTPbuild to specify the tasks and node-local messages.

A.2.3 Application Programming

Now it is time to do the actual programming and implement algorithms. One function for each task that is run on a node has to be implemented. The TTPos provides a set of API calls that can be used to access messages and information about the cluster and the node.

Here some of the weak spots and immature nature of the TTP products show up. Some functions are yet to be implemented and some things are a bit cumbersome to achieve. There are, for example, possible to define several "cluster modes"[2] in TTPplan, but there are no way to change the currently active cluster mode. This will probably change in a later release of the operating system.

A.2.4 Transferring schedule and applications to the cluster

The schedule is transferred to the cluster with the help of another TTPtool, namely TTPload. This application uses a dedicated node, a monitoring node or download master node, which act as a bridge between the cluster and a PC with a standard Ethernet card.

TTPload will, however, only download the schedule and not the application. This must be transferred directly to each node via a so called BDM-cable. The BDM-cable puts the host processor in a special debug mode which allows access to the nodes flash memory.

[2]All cluster modes have different schedules and thus can send another set of messages and run other tasks. One use could be to set the cluster in some sort of service mode which allows for debug output and sensor calibration.

A.2.5 Running and debugging the cluster

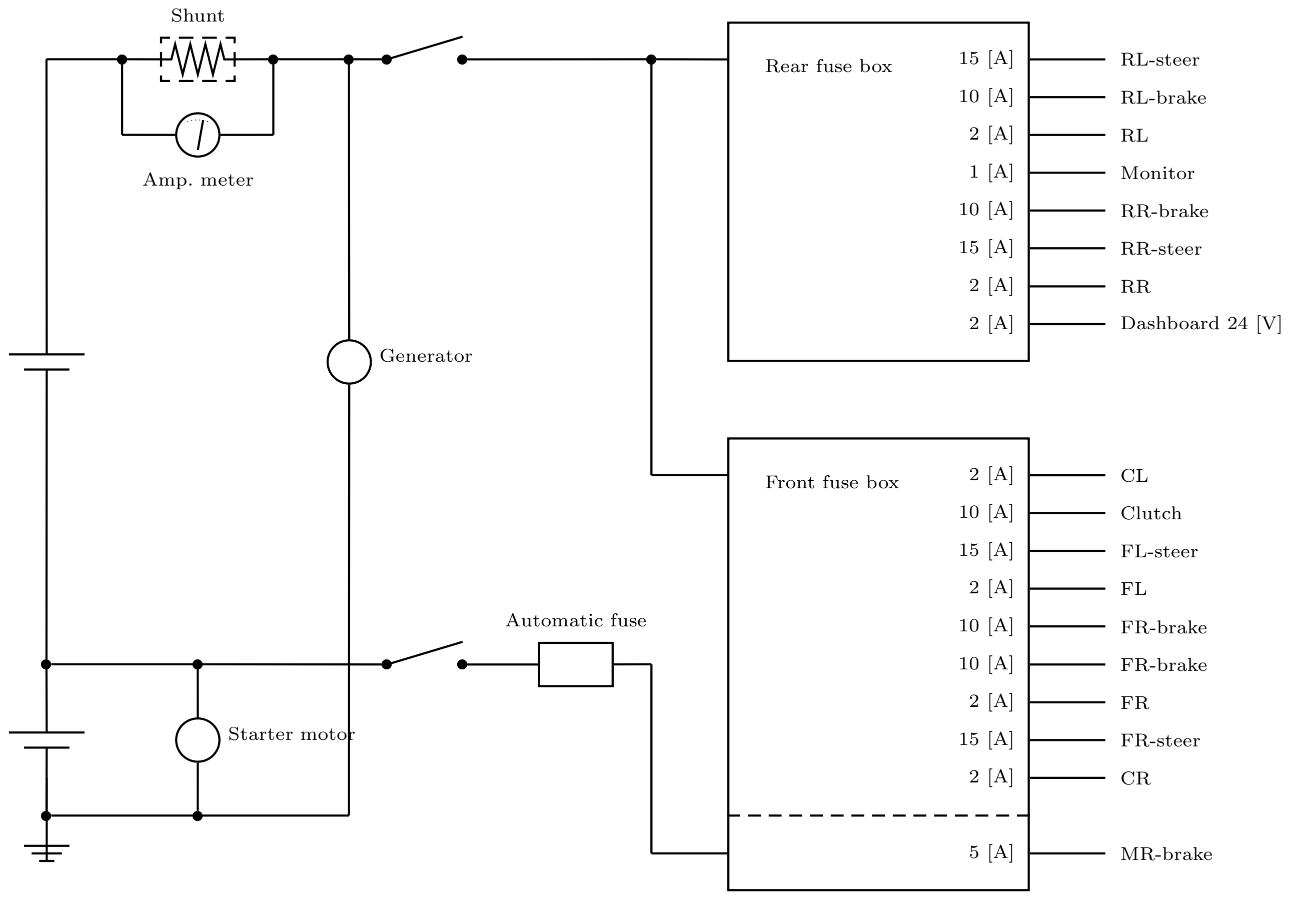
After the schedule and application data are transferred the cluster should be ready to be started. If everything works, each node should blink a green led to indicate that it has contact and is synchronized with the network.

Debugging and monitoring can be done with a tool called TTPview which gives access to all of the global messages in the cluster. These can be shown as different kinds of instruments such as LEDs and graphs. Each node can additionally be debugged with a debugging software and the BDM-cable mentioned earlier. This approach does not, however, give access to the information on the network.

Appendix B

System Power Schematic

This appendix contains an overview of the power system in the car. Note that only the parts involved in the X-by-Wire system is specified.


Shunt
Amp. meter
Generator
Starter motor
Automatic fuse
Rear fuse box
15 [A] RL-steer
10 [A] RL-brake
2 [A] RL
1 [A] Monitor
10 [A] RR-brake
15 [A] RR-steer
2 [A] RR
2 [A] Dashboard 24 [V]
Front fuse box
2 [A] CL
10 [A] Clutch
15 [A] FL-steer
2 [A] FL
10 [A] FR-brake
10 [A] FR-brake
2 [A] FR
15 [A] FR-steer
2 [A] CR
5 [A] MR-brake

Appendix C

Circuit Board Diagrams

This appendix shows the diagrams for the adapting electronics between the TT-Tech PowerNodes and the sensors and actuators. Figure C.1 show the boards in the wheel nodes, Figure C.2 in Node CL and Figure C.3 in Node CR.

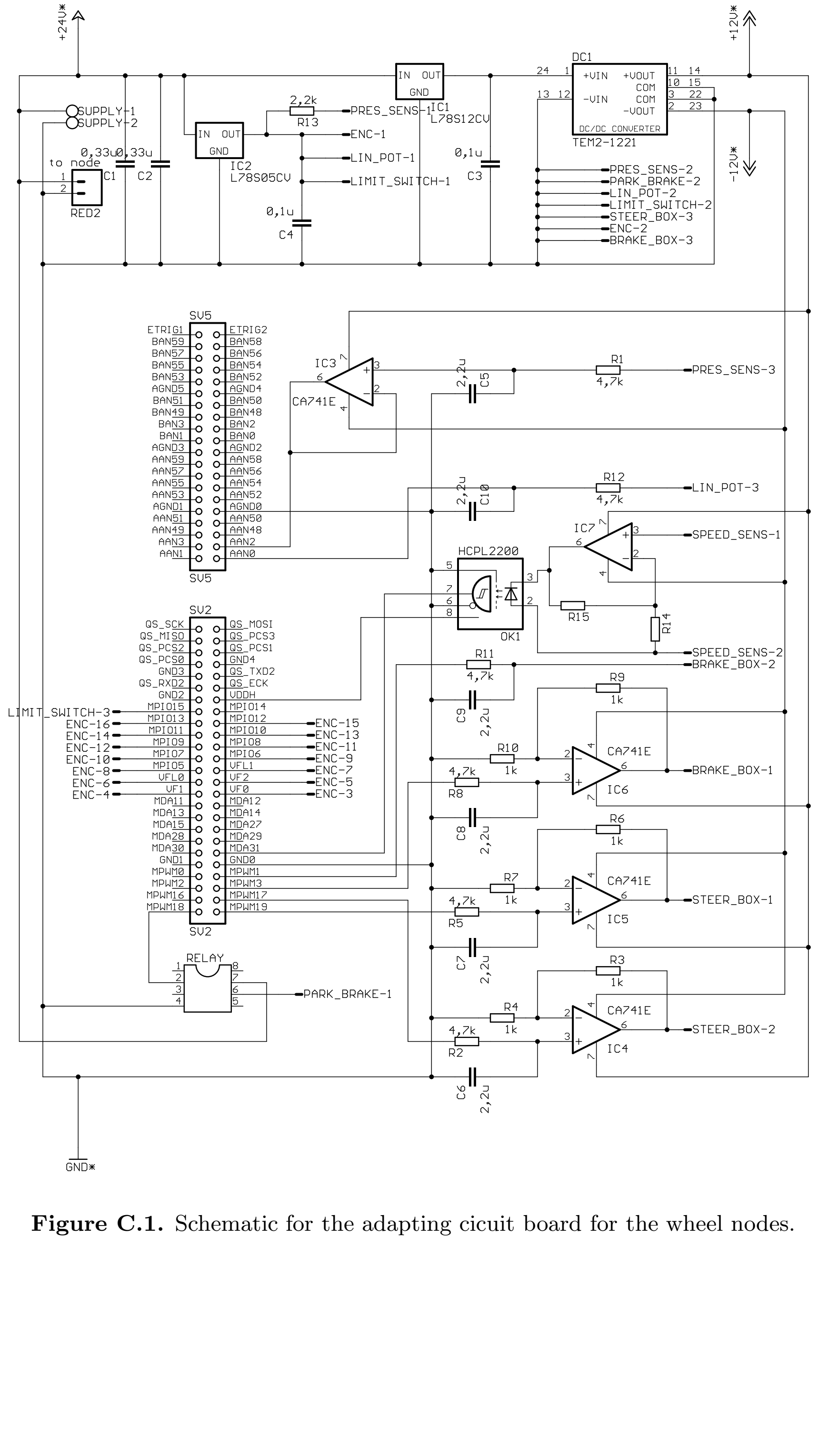


Figure C.1. Schematic for the adapting cicuit board for the wheel nodes.

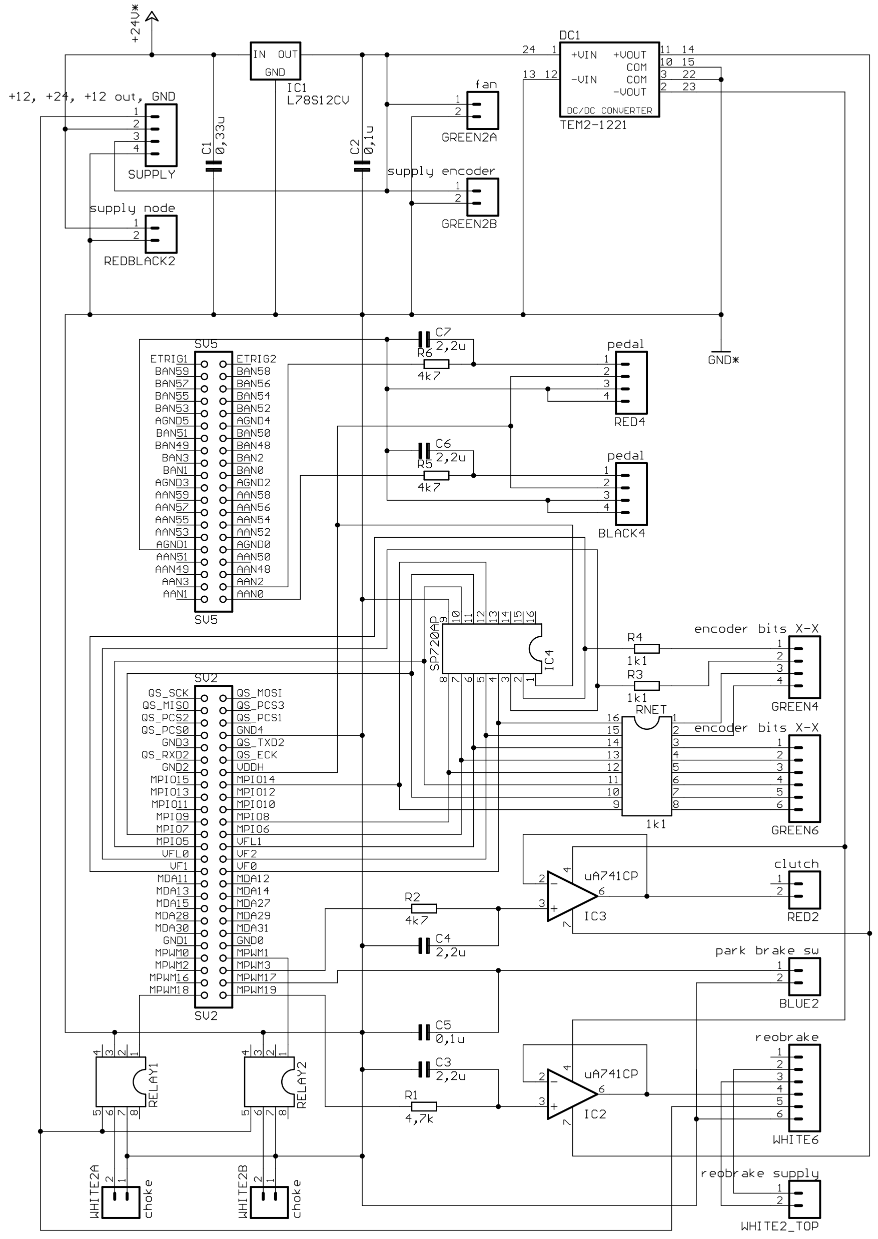


Figure C.2. Schematic for the adapting cicuit board for Node CL.

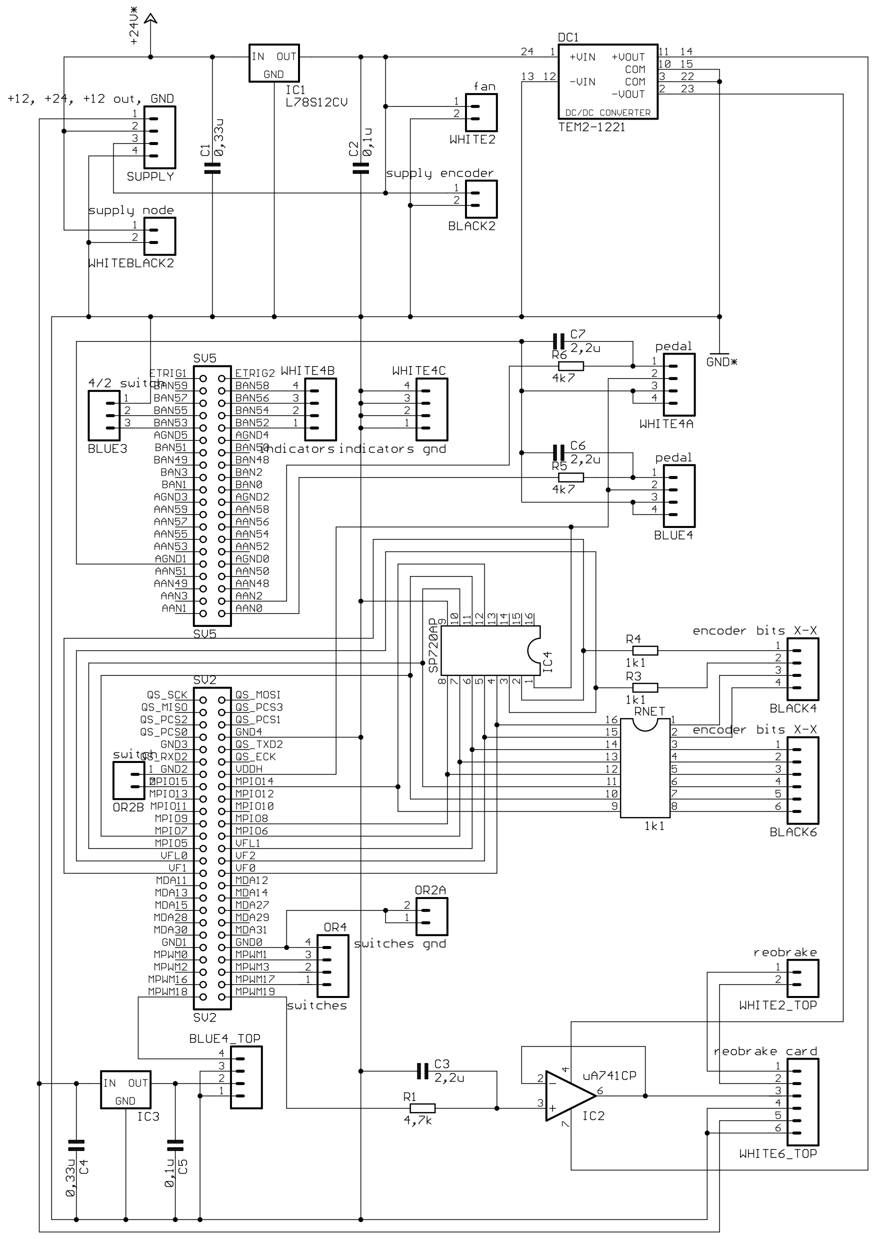


Figure C.3. Schematic for the adapting cicuit board for Node CR.

Appendix D

Circuit Board Connections

Below, detailed descriptions on how to connect the different sensor and actuator wires found in each of the nodes, are given.

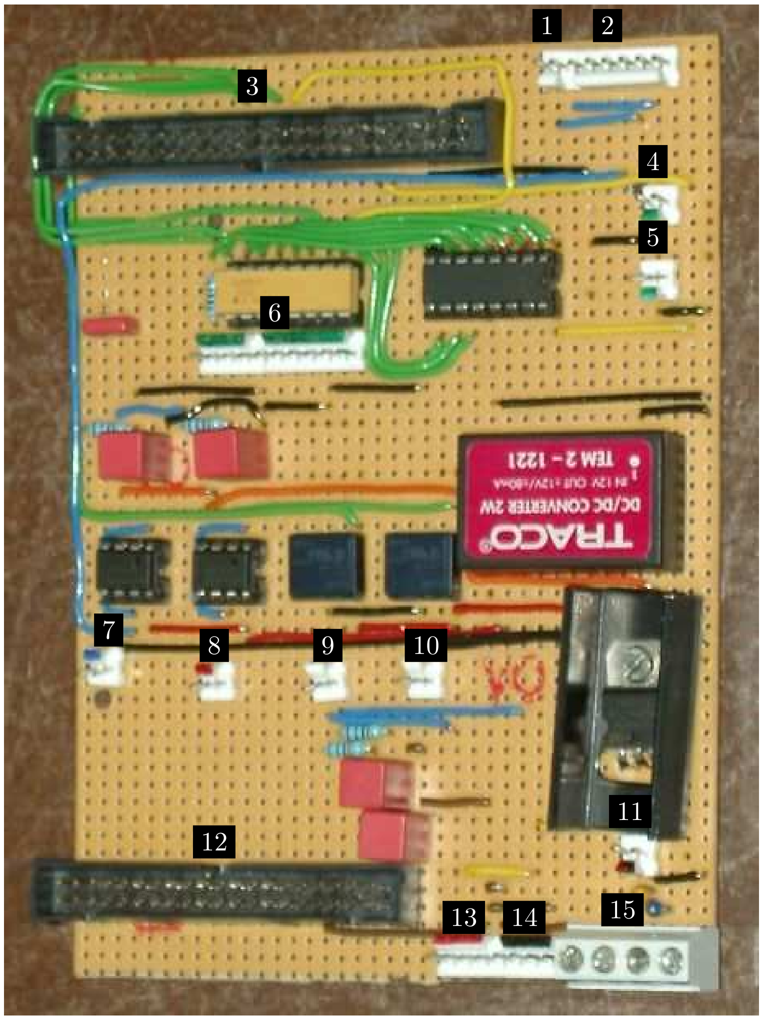


Figure D.1. Circuit board wire connections for Node CL. The numbers are specified in Table D.1.

Table D.1. Node CL circuit board connections. Below is the description to the numbers in Figure D.1. The connectors are specified, when appropriate, from left to right.

Number	description		
1	Brake pedal MR-brake		
2	MR-brake controller card		
3	50 pin PowerNode connector		
4	Housing fan power supply		
5	Steering wheel encoder power supply		
6	Steering wheel encoder signal output		
7	Parking brake dash board switch		
8	Clutch actuator reference input		
9	Carburettor choke forward		
10	Carburettor choke retract		
11	PowerNode power supply		
12	40 pin PowerNode connector		
13	Brake pedal sensor		
14	Clutch pedal sensor		
15	Board power supply;	+ 12 V	brown
		+ 24 V	red
		+ 12 V out	n/a
		GND	black

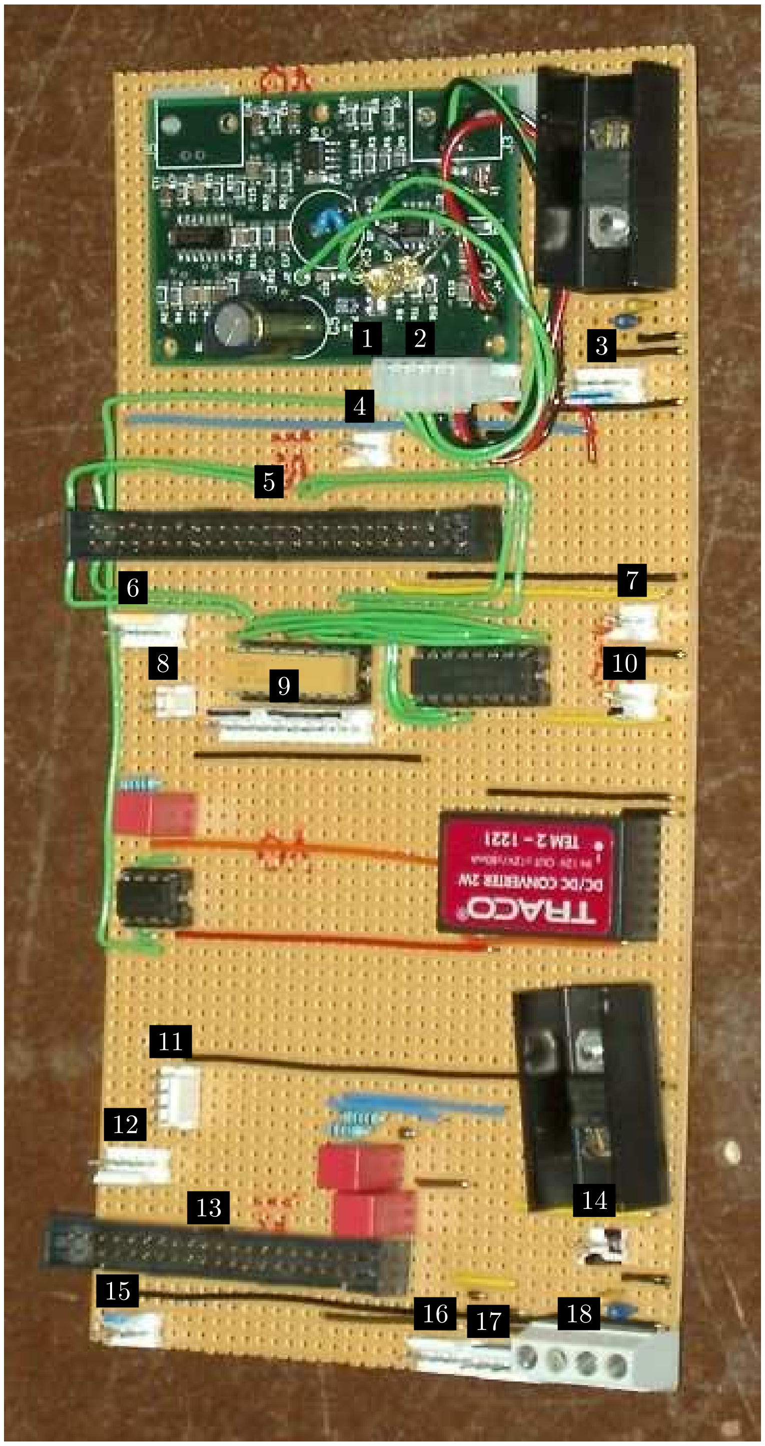


Figure D.2. Circuit board wire connections for Node CL. The numbers are specified in Table D.2.

Table D.2. Node CR circuit board connections. Below is the description to the numbers in Figure D.2. The connectors are specified, when appropriate, from left to right.

Number	Description		
1	Steering wheel MR-brake		
2	MR-brake controller card		
3	Carburettor throttle valve servo		
4	2-way dash board switch		
5	50 pin PowerNode connector		
6	2-way dash board switches (three in total)		
7	Housing fan power supply		
8	2-way switches GND		
9	Steering wheel encoder signal output		
10	Steering wheel encoder power supply		
11	Dash board LED:s GND		
12	Dash board LED:s (four in total)		
13	40 pin PowerNode connector		
14	PowerNode power supply		
15	3-way dash board switch		
16	Accelerator pedal sensor		
17	Brake pedal senor		
18	Board power supply;	+ 12 V	brown
		+ 24 V	red
		+ 12 V out	n/a
		GND	black

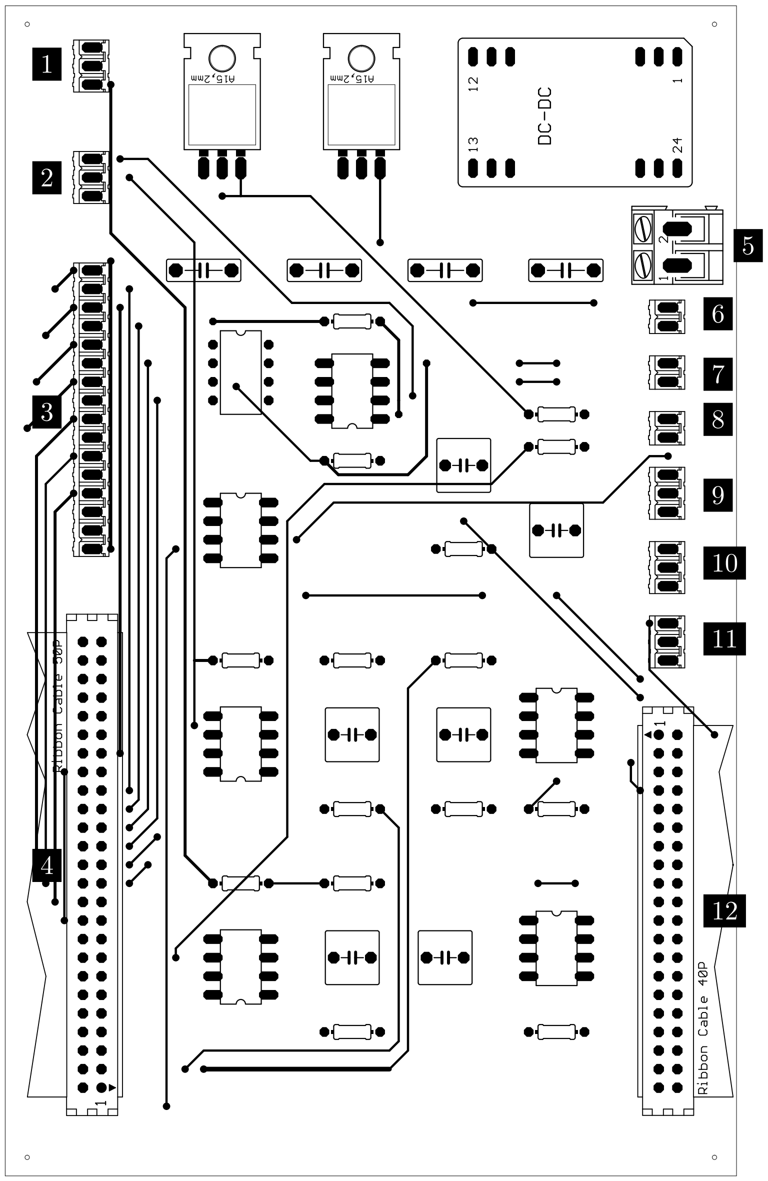


Figure D.3. Circuit board wire connections for the wheel nodes. The numbers are specified in Table D.3.

Table D.3. The description to the numbers in Figure D.3. Each connector is specified (when appropriate), together with the corresponding wire colours, from the top and down (refer to Figure D.3). Note the connection of the pressure sensor. The peculiar wiring is due to a mistake when the boards were made.

Number	Description			
1	Wheel angle actuator;	GND	black	
		set value -	blue	
		set value +	red	
2	Linear position sensor;	signal	green	
		GND	white	
		+ 5 V	brown	
3	14 bit wheel angle encoder;	bit 13	brown/green	
		bit 12	white/black	
		bit 11	white/red	
		bit 10	white/blue	
		bit 9	white/pink	
		bit 8	white/grey	
		bit 7	white/yellow	
		bit 6	white/green	
		bit 5	white/brown	
		bit 4	violet	
		bit 3	red/blue	
		bit 2	brown/grey	
		bit 1	brown/yellow	
		bit 0	grey/pink	
		GND	black	
		+ 5 V	red	
4	50 pin PowerNode connector			
5	Board power supply;	GND	black	
		+ 24 V	red	
6	PowerNode power supply;	GND	black	
		+ 24 V	red	
7	Speed sensor			
8	Parking brake lock			
9	Pressure sensor;	signal	red	
		GND	green	
		supply	red	(connect this to the "signal" pin)
10	Brake actuator;	GND	black	
		set value -	blue	
		set value +	red	
11	Limit switch;	signal	black	
		GND	grey	
		+ 5 V	blue	+ pressure sensor blue
12	40 pin PowerNode connector			

Appendix E

Manufacture Drawings

In this Appendix, all the manufacture drawings of the fabricated parts have been included. In Figure E.1 to E.4 the parts of the modified steer actuator joint are shown, and E.5 to E.9 displays the attachment parts of the front actuator control box. The last two figures, Figure E.10 and E.11, shows the parts of the rear control box attachment.

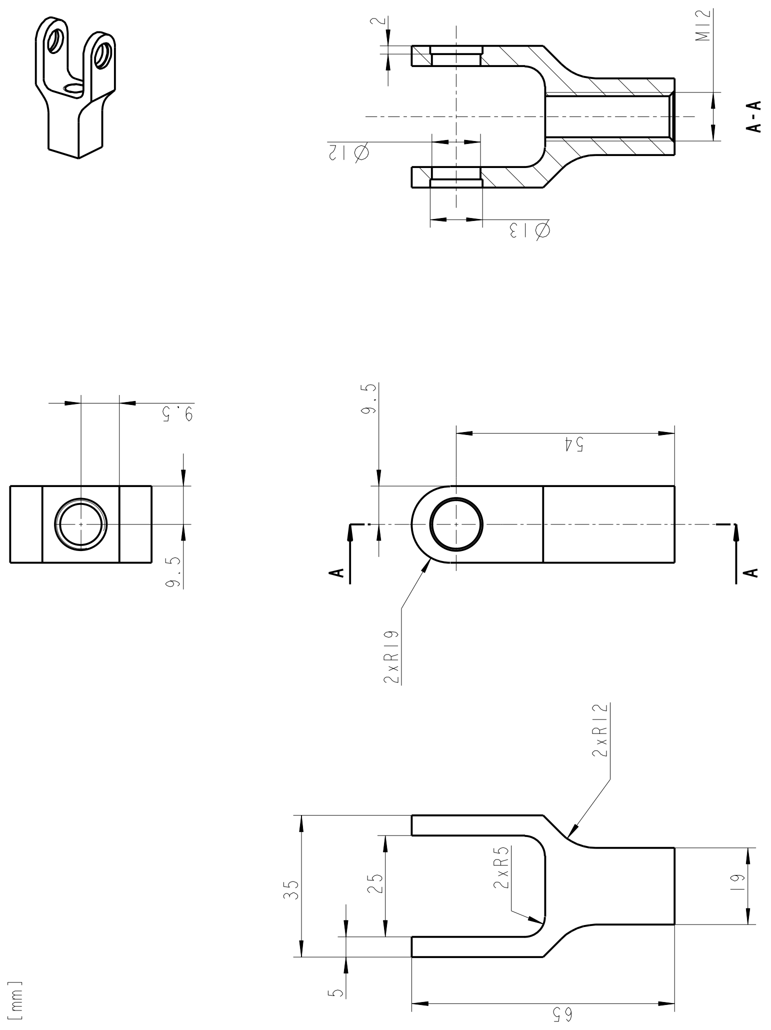


Figure E.1. Steer actuator universal joint — the joint fork.

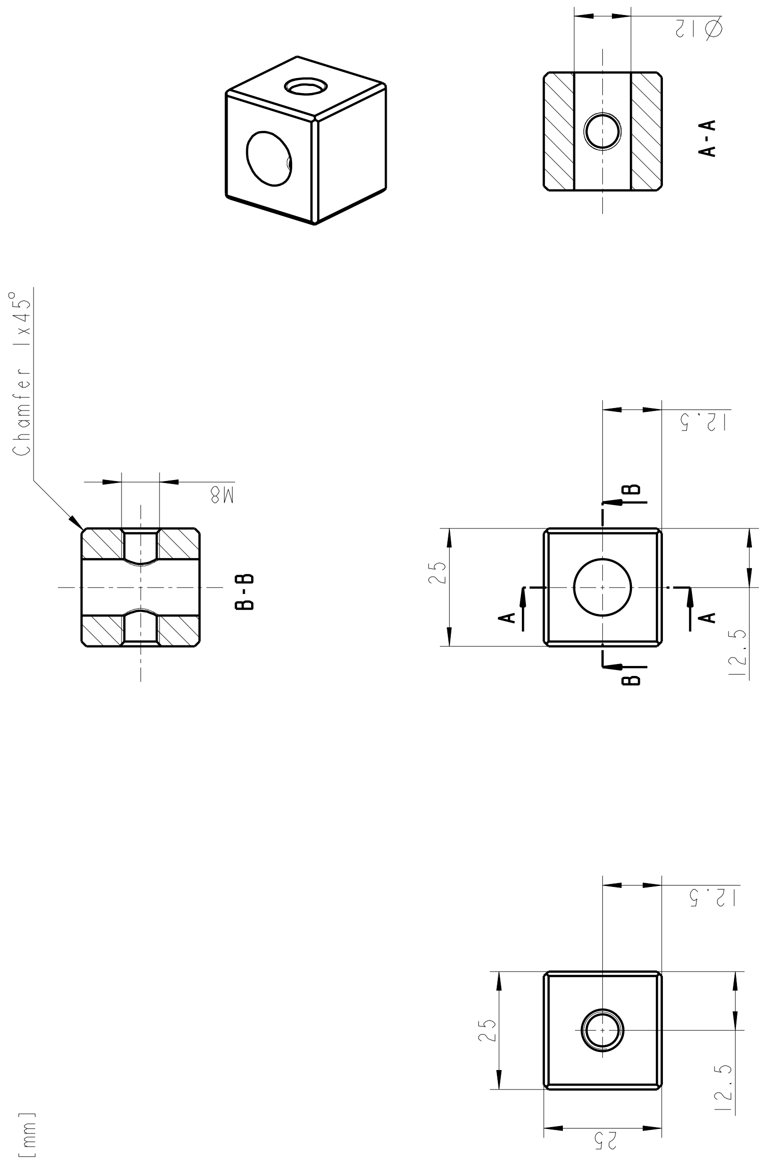


Figure E.2. Steer actuator universal joint — the joint centre cube.

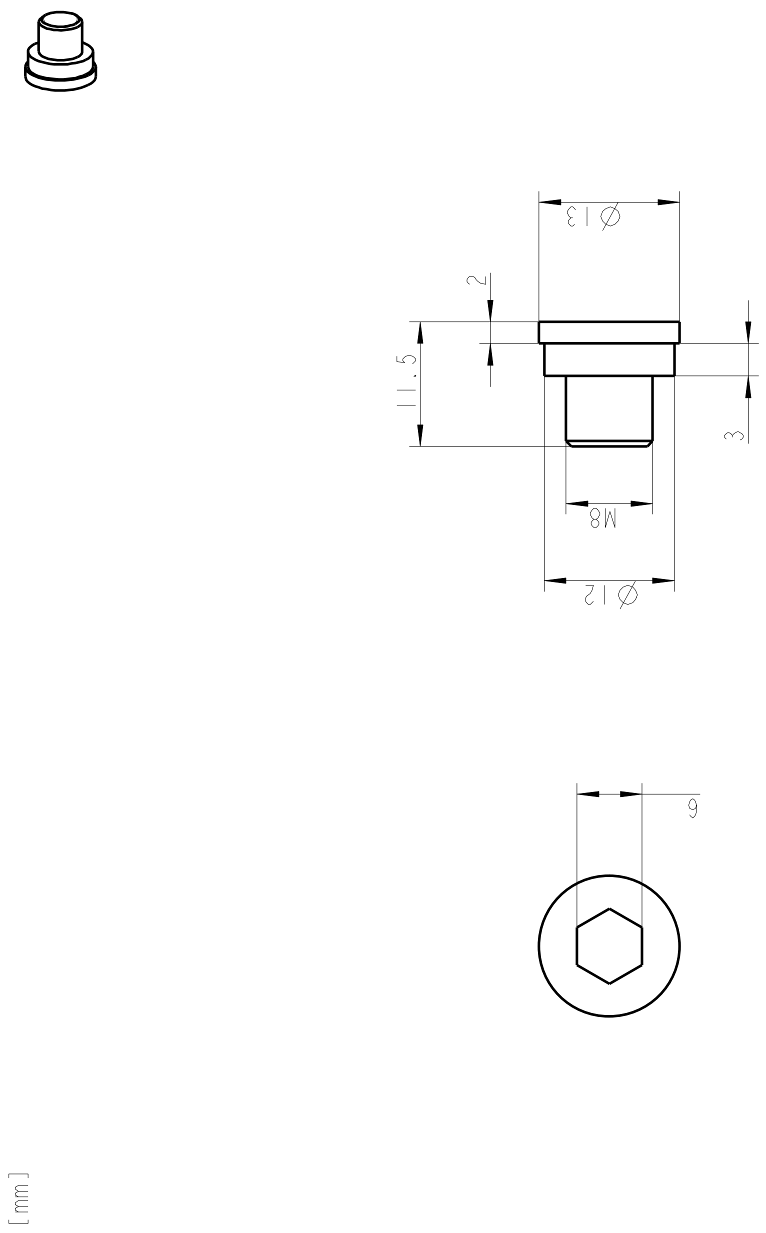


Figure E.3. Steer actuator universal joint — the screw that joins the fork to the centre cube.

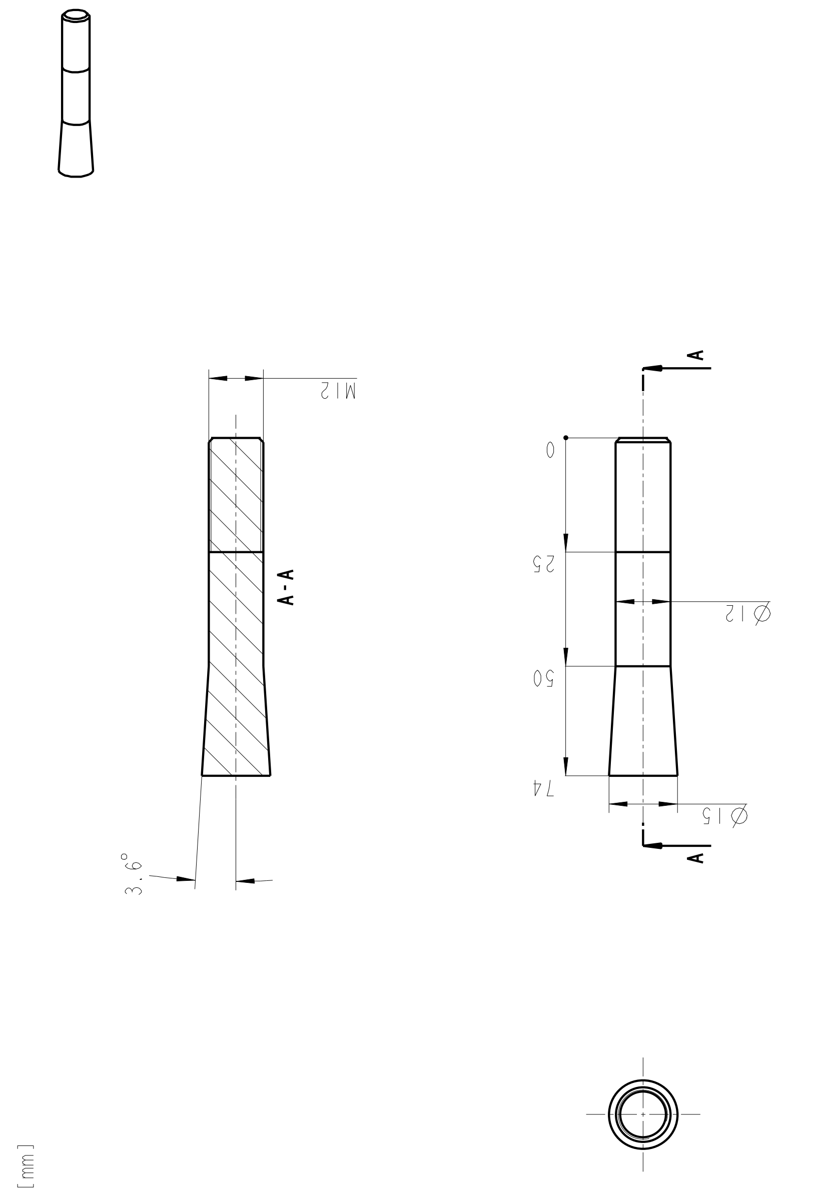


Figure E.4. Steer actuator universal joint — the clevis pin used to attach the joints to the front wheel spindles.

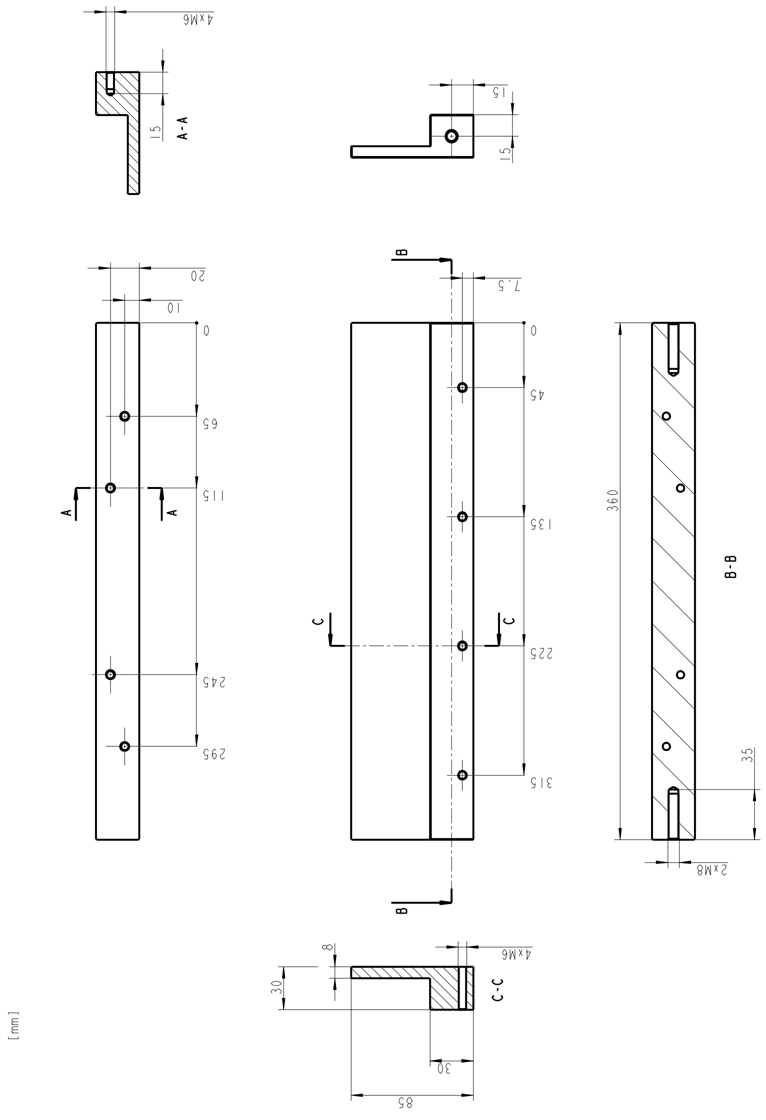


Figure E.5. Front control box attachment — the attachment base.

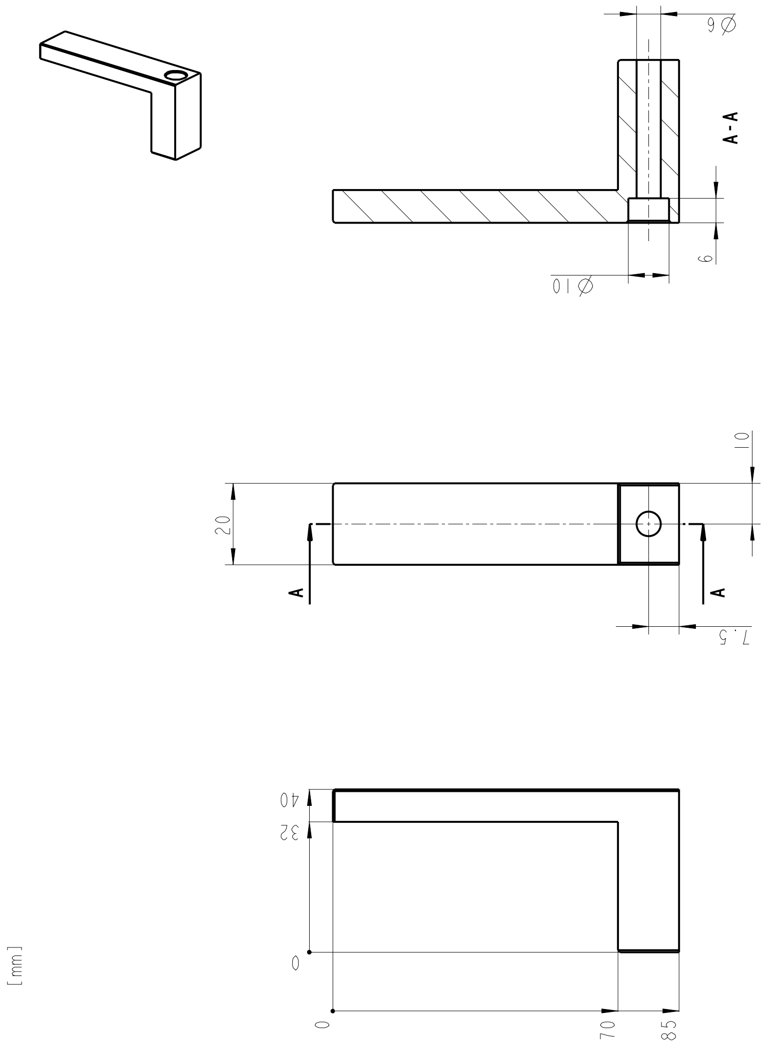


Figure E.6. Front control box attachment — the attachment clamp.

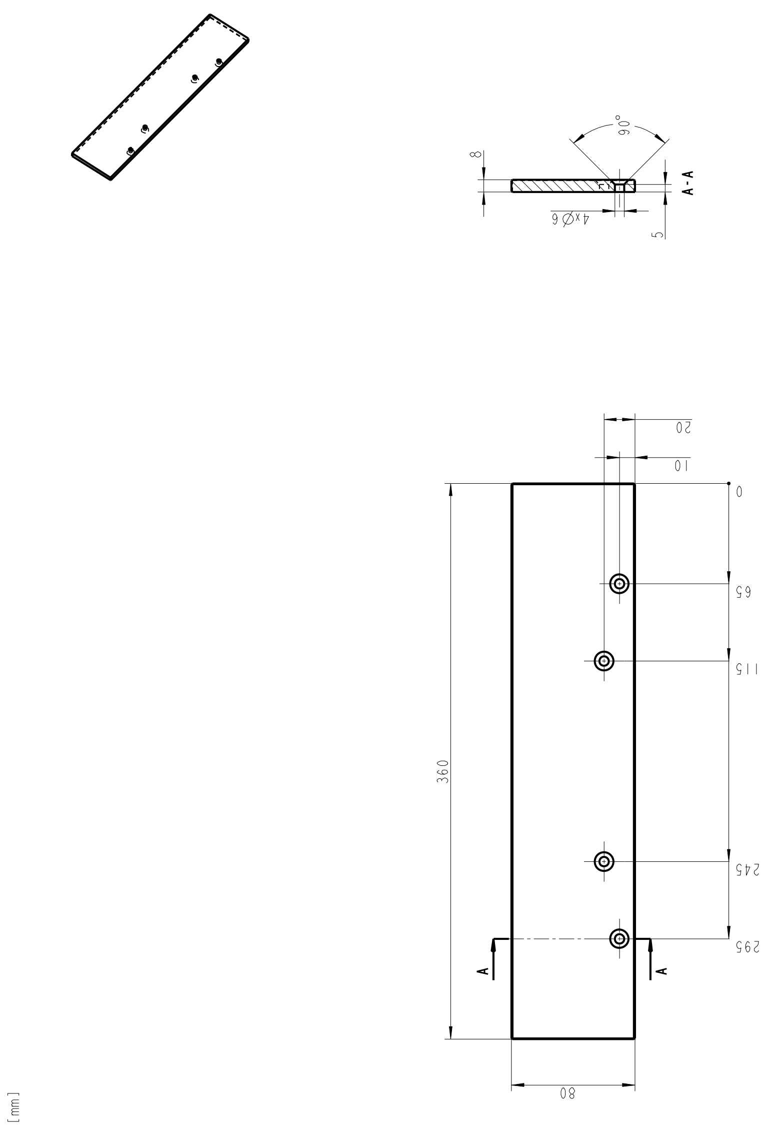


Figure E.7. Front control box attachment — the clamp support.

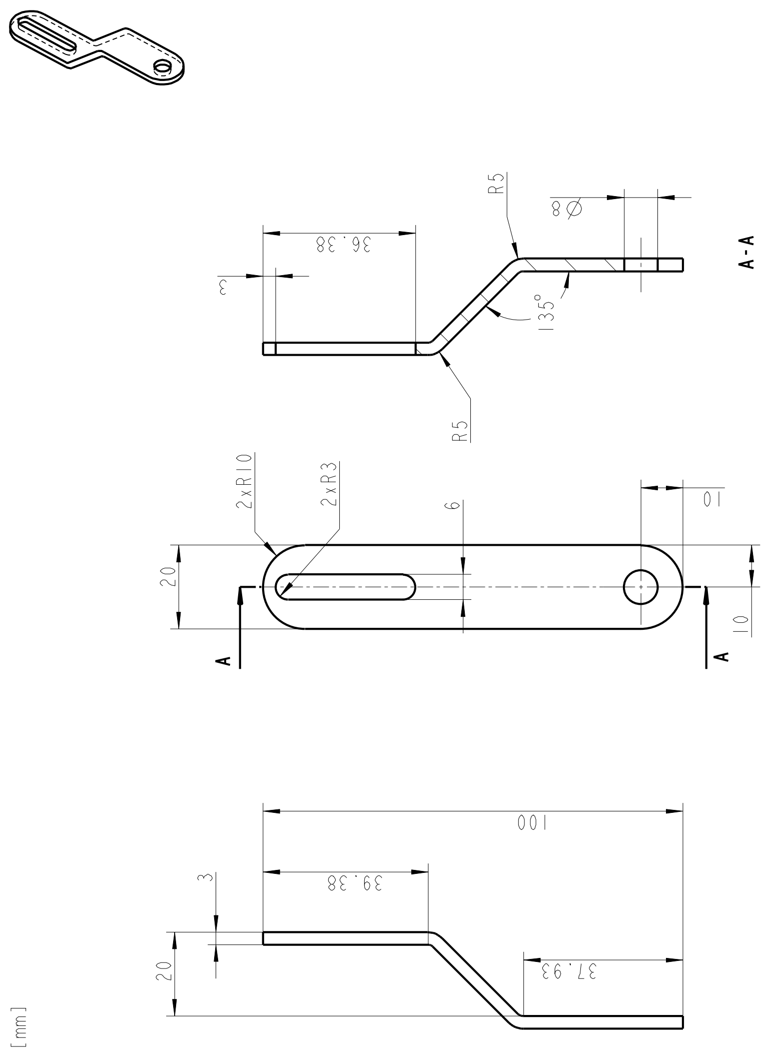
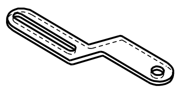


Figure E.8. Front control box attachment — the short bracket (fixes the attachment base in the car).



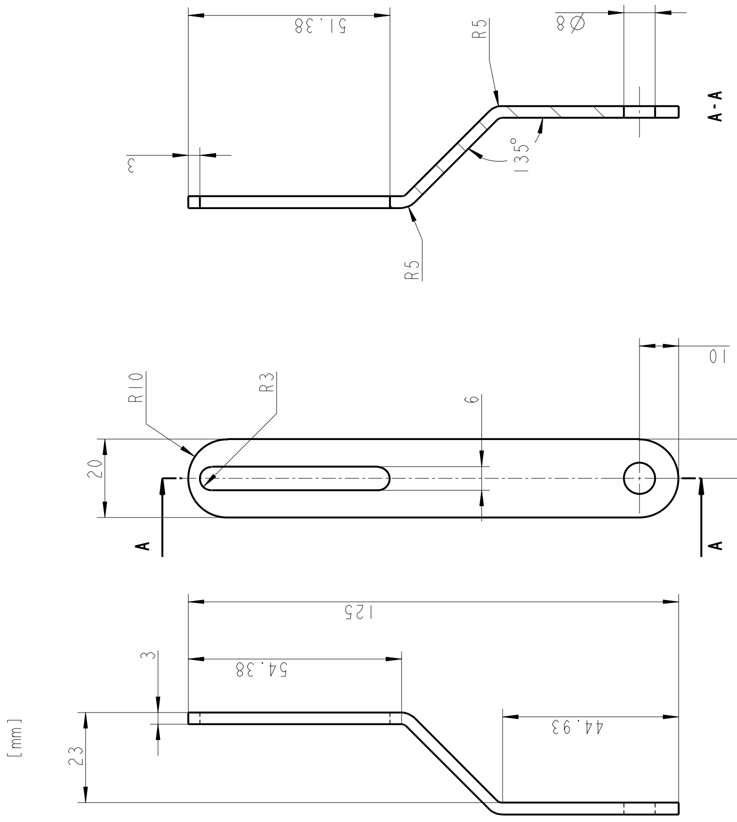


Figure E.9. Front control box attachment — the long bracket (fixes the attachment base in the car).

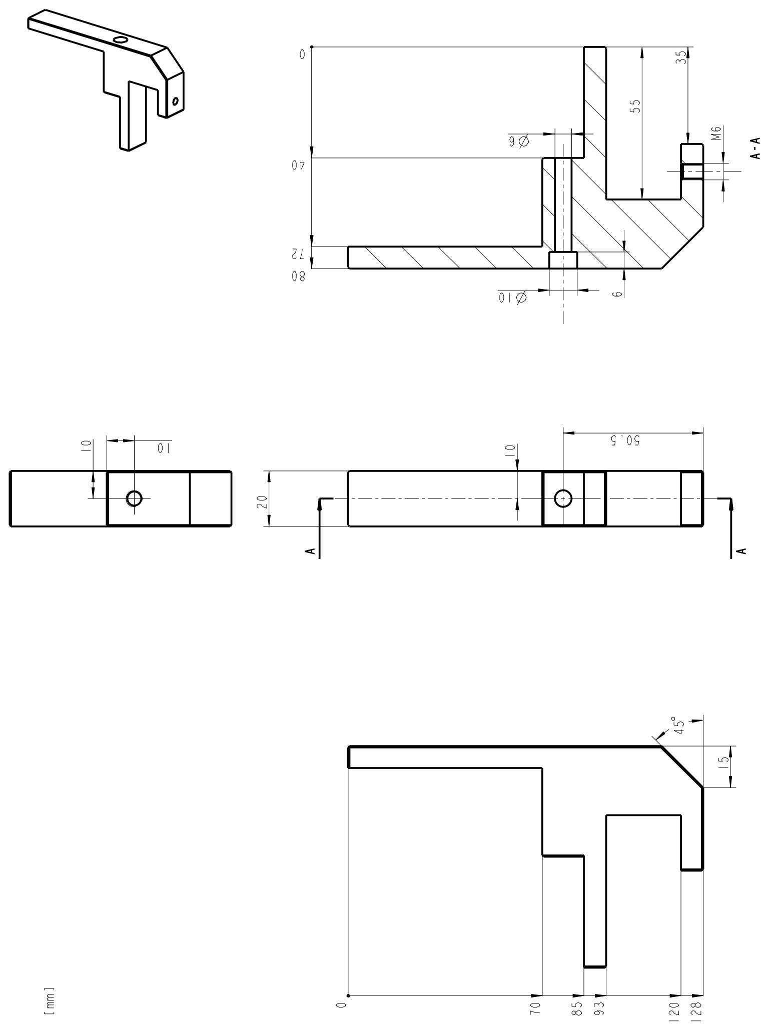


Figure E.10. Rear control box attachment — the attachment base.

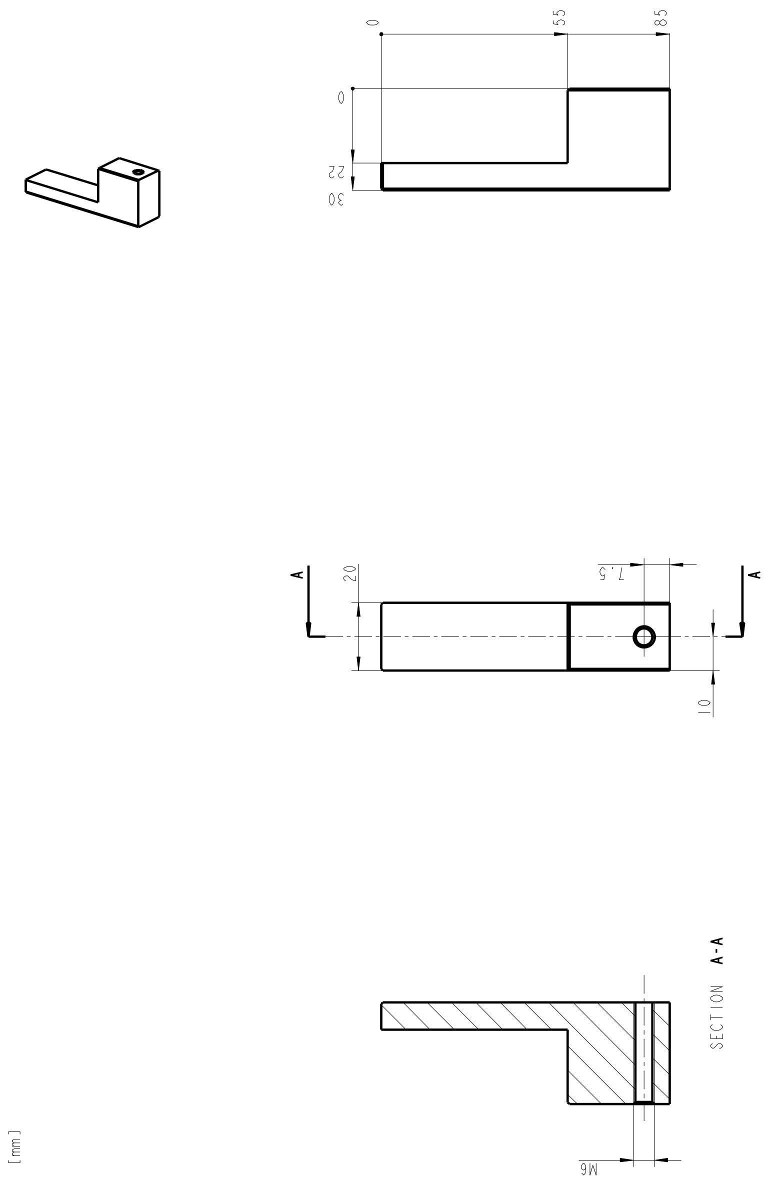


Figure E.11. Rear control box attachment — the attachment top.