

Semester-Project

Communication with a Toyota Prius

Decoding of the CAN Protocol and
Development of a Graphical Interface

Autumn Term 2009

Contents

List of Tables	iii
List of Figures	v
Abstract	vii
Symbols	ix
1 Introduction	1
2 Related Work	3
2.1 My CAN Project	3
2.2 Team-LUX	3
2.3 SmartTer	4
3 Toyota Prius - Background	7
3.1 Hybrid Synergy Drive	7
3.1.1 Functionality	8
3.1.2 Hybrid Vehicle Control System	10
3.2 Controller Area Network	11
3.2.1 Multiplex-Communication Systems	11
3.2.2 CAN Protocol	12
3.3 CAN in the Prius	13
4 Methodology	17
4.1 Connection to the CAN	17
4.2 Messages Analysis	17
4.3 Control Actuators	20
5 Results	23
5.1 Results of Messages Analysis	23
5.2 Results of Control Actuators	24
6 Conclusion and Further Work	27
Bibliography	29

List of Tables

3.1	Properties of the Prius MPXs.	11
3.2	Base frame format	13
5.1	ID and content of CAN messages.	23

List of Figures

2.1	Side view of the SmartTer	4
2.2	SmartTer <i>steer-by-wire</i> system diagram.	5
3.1	Toyota Prius NHW20 side view.	7
3.2	Toyota <i>Hybrid Synergy Drive</i> logo.	8
3.3	Simplified cross section of the hybrid transaxle.	9
3.4	Diagram of the HSD communication system.	10
3.5	Diagram of a CAN	12
3.6	Schema of the Prius CAN bus.	14
3.7	Location of CAN components.	15
4.1	CPC-USB device.	17
4.2	Connection between laptop and DLC3 port.	18
4.3	Example of the monitoring tool.	19
4.4	Course of the steering angle value of <code>0x25</code> and <code>0x264</code>	21
5.1	GUI displaying several states of the Prius.	24
5.2	CAN diagram of EPS.	25
5.3	CAN diagram of the gearshift.	25
5.4	CAN diagram of the signal from the gaspedal to the throttle valve.	26

Abstract

In the context of autonomous car navigation, the Autonomous System Lab (ASL) of the ETH Zurich is willing to build a new research platform. For this purpose, a Toyota Prius has been bought. The first required step to turn the Prius into an autonomous car is to have an electronic access to its low-level functions such as the steering, the brakes, the gas and the gear. This report is focused on analyzing the feasibility to display and control car states via the vehicle's CAN bus.

The interface with the CAN bus was achieved by a CPC-USB device connected with a RS232 connector to the DLC3 diagnostic port of the CAN-Bus. In a first step, existing CAN-Messages has been identified and their content interpreted. Also their reliability has been investigated. It turned out that the RS232 port has a lower transfer rate than the CAN bus. Thus, the frequency of the received messages was not constant. Based on the knowledge of the existing messages we duplicated and modified the messages and sent them onto the CAN bus in order to change the car status. The dissatisfying results revealed that car states can not be influenced by the CAN bus with a sufficient behavior. We were able to change the position of the steering wheel, but other states could not be influenced by CAN messages with a satisfying result without modifying the CAN bus.

The CAN bus may be used for displaying car states. It is advisable to connect your system directly to the CAN bus via the connection assembly. To control car states direct electronic links to the corresponding sensors or actuators should be used in order to achieve acceptable results.

Symbols

Symbols

δ	steering wheel angle offset
ϕ	steering wheel angle
b_i	decimal value of the byte i

Acronyms and Abbreviations

ASL	Autonomous System Lab
CAN	Controller Area Network
ECU	Electronic Control Unit
EPS	Electric Power Steering
ETH	Eidgenoessische Technische Hochschule
HSD	Hybrid Synergy Drive
ICE	Internal Combustion Engine
IMU	Inertial Measurement Unit
ID	Identifier
IPAS	Intelligent Parking Assist System
MG1	Motor-Generator 1
MG2	Motor-Generator 2
MPX	Multiplex-Communication System
ODB	On-Board Diagnostics
SOC	State Of Charge

Chapter 1

Introduction

In the context of autonomous car navigation, the Autonomous System Lab (ASL) of the ETH Zurich is building a new research platform based on the knowledge acquired in the earlier project called SmartTer [1]. The SmartTer was equipped with a *drive-by-wire* system to control the gas pedal, the brake pedal and the steering wheel from a central computation unit. Based on that, research on autonomous driving and mapping becomes possible.

To enable autonomous driving with the new vehicle, the Toyota Prius, it is required to have an electronic access to its low-level functions such as the steering, braking, acceleration and gear shifting. The aim of this report is to determine the feasibility of displaying important sensory information and controlling the basic functions of the car via the vehicle's CAN. This should be done without modifying the CAN bus and ECUs. Some car states (e.g. car speed, steering angle, etc.) can be used as feedback signals for high-level and low-level control. Therefore, the reliability, accuracy and precision of the sensor data provided by the CAN bus have to be verified. In a further step, messages has to be sent to the CAN bus in order to control certain actuators of the car such that the steering, accelerating, decelerating and gear shifting becomes possible.

In the first step, the access to the CAN bus of the vehicle has to be enabled. Afterwards, transmitted data has to be received, identified and their content converted into useful information. On the one hand, that provides important information about the car states. On the other hand, the comprehension of the messages provides information about the communication between the connected devices. This is required for the next step. Once the messages, their content and their properties are known, it is possible to send self-generated messages onto the CAN bus in order to control car states.

This report is structured as follows. In Chapter 2 related projects are presented. The next chapter summarizes the findings of the background investigation. It contains information about the Toyota Prius and *full-hybrid* car technology. It also introduces the CAN protocol and the usage of the CAN in the Toyota Prius. Chapter 4 describes our procedure. It starts with connecting our computation unit to the CAN bus, followed by analyzing received messages and sending messages onto the CAN. Chapter 5 shows the results of this project.

Chapter 2

Related Work

In order to turn the Prius into an autonomous vehicle the electronic access to the low-level functions of the car is required. This chapter presents related projects where vehicles are controlled with a *drive-by-wire* system.

The first section introduces a project that focuses on reading CAN messages of a Toyota Prius 2004. Section 2.2 shows how a VW Passat was turned into an autonomous car. The last section presents the SmartTer. A standard Smart car that was modified in such a way that autonomous navigation becomes possible.

2.1 My CAN Project

Attila Vass [2] worked with an Toyota Prius 2004. This is an older version of the Prius than we are working with. He wanted to get more information about the car status than it was given on the standard display. He connected to the CAN via the OBD connector with and CAN232-USB serial. Vass was able to read the following states of the car:

- engine speed
- engine and coolant temperature
- battery state of charge, voltage and temperature
- gas gauge, throttle, speed
- two acceleration sensors
- rotation speeds on individual wheels
- brake, gas pedal and steering wheel values

With an on-board computer he displayed online all the desired Prius states during driving. He provides on his website his findings of the CAN messages. In this project we used, verified and extended his information about the CAN messages.

2.2 Team-LUX

The autonomous car LUX was developed for the Defense Advanced Research Projects Agency (DARPA) Urban Challenge by the sensor and laser scanner producers Ibeo and SICK [3]. DARPA Challenges are field tests of autonomous ground vehicles over different terrain.

The LUX is a VW Passat 2.0 TDI built in 2006. The autonomous control equipment is fully integrated into the vehicle (i.e. the car may be driven by a driver). The breaking system is a servo tube, which can operate the brake pedal just like a driver. This electromechanical braking system is controlled by an on-board computer. The so-called E-Gas module is an electrical switch which is built in between the gas pedal and the motor control device. Control commands are sent from the main computation unit through the vehicle's CAN bus to the respective control units. For steering, a special motor was installed which is connected with a timing belt to the steering column. Also commands for steering are sent via the CAN bus and converted with 0.5 degree accuracy into a turning motion of the steering wheel. The turning rate, the torque and the desired position can be given. Also the electronic gear shifter can be controlled via CAN with a similar function method as the E-Gas. An electronic switch is connected between the automatic gear shift and the gearbox control device. During autonomous driving, the actual position of the gear shift (P, R, N or D) does not matter.

2.3 SmartTer

The SmartTer (Smart all Terrain) is the predecessor of the Toyota Prius. The main idea of the SmartTer was to construct a hardware platform that allows to perform the task of autonomous navigation in large scale outdoor environments. A standard Smart car was modified in such a way that all necessary characteristics for autonomous navigation and mapping are included.

Driving the car with a *drive-by-wire* system was enabled. Moreover, the car was equipped with five distance laser sensors, two cameras, an omni directional camera, a differential GPS, an Inertial Measurement Unit, an optical gyroscope and four computer racks. The fully equipped SmartTer is depicted in Figure 2.1. Since the



Figure 2.1: Side view of the SmartTer [1].

Smart was equipped with a power steering motor that has enough torque to steer the car, it was possible to *steer-by-wire*. The smart already has an auto gearshift. Thus, no additional modifications were required to switch gears while the car was driving. The Smart was already equipped with a CAN bus. The vehicle CAN bus provided important sensory information such as the steering wheel angle and wheel velocities. These features facilitate the process of converting such a vehicle for autonomous driving.

In Figure 2.2 the diagram of the *steer-by-wire* system is shown. For this system, a specific electronic board has been designed. In order to use the power steering motor of the Smart its control unit (DA unit) was disconnected from the vehicle CAN bus and routed to a computer (Rack0). An additional CAN bus (Computer CAN) was installed to feed the DA unit with CAN messages. The electronic board enables the use of a computer to set the gas and the steering wheel commands. The Computer CAN sends commands to a CAN-to-analog module which fakes the torque voltage of the steering column torque sensor and the position voltage of the gas pedal position sensor needed by the DA unit. A switch allows to choose between normal or controlled mode. A servo motor was used to activate the brake pedal.

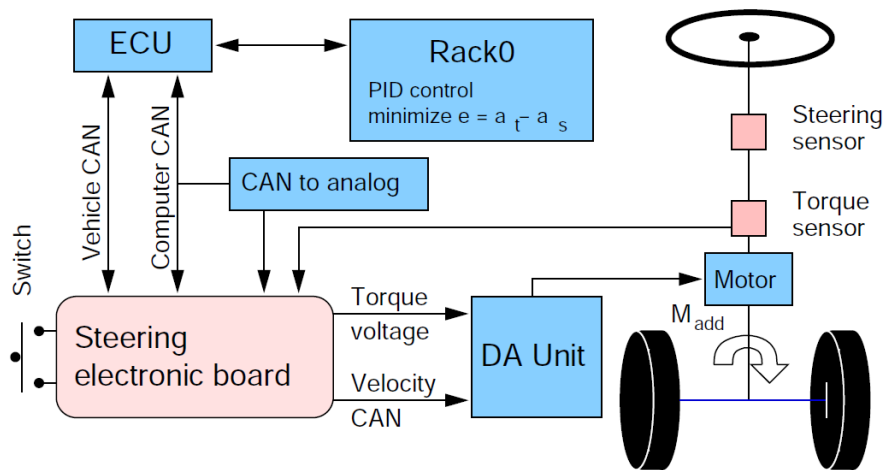


Figure 2.2: SmartTer *steer-by-wire* system diagram [1].

Chapter 3

Toyota Prius - Background

During this project we were working with a Toyota Prius NHW20, model year 2006. A picture of the car is shown in Figure 3.1. The Toyota Prius (short Prius) is a *full hybrid* electric mid-size car developed and manufactured by the Japanese Toyota Motor Corporation [4]. It first went on sale in Japan in 1997 and was the first mass-produced hybrid vehicle. It was subsequently introduced worldwide in 2001. The Prius is sold in more than 40 countries and regions. In May 2008, global cumulative Prius sales reached the 1 million vehicle mark.



Figure 3.1: Toyota Prius NHW20 side view [10].

The first section of this chapter presents the Hybrid Synergy Drive of Toyota. Section 3.2 gives an overview of the Controller Area Network. The usage of the CAN bus in the Prius is described in the last section.

3.1 Hybrid Synergy Drive

The Hybrid Synergy Drive (HSD) is a set of hybrid car technologies developed by Toyota which allows the realization of a *full hybrid* vehicle [5]. That allows the car to perform on the electric motor only as opposed to other, so called *mild hybrid*, cars can not. The electric motor of *mild hybrid* cars only supports the Internal

Combustion Engine (ICE) with additional torque. A *full hybrid* vehicle combines an electric propulsion system and a continuously variable transmission with the ICE. The HSD is a *drive-by-wire* system with no direct mechanical connection between the engine and the engine controls: both, the gas pedal and the gear shift lever send electrical signals to a control unit.



Figure 3.2: Toyota *Hybrid Synergy Drive* logo [10].

In the standard car design the alternator (AC generator) and starter (DC motor) are considered accessories that are attached to the ICE. The ICE drives a transmission to power the wheels. A battery is used only to start the internal combustion engine of the car and runs accessories when the engine is not running. The alternator is used to recharge the battery when the engine is running. The HSD technology replaces the conventional gear box, alternator and starter with:

- a pair of powerful motor-generators (MG1 and MG2) with a computerized shunt system (HV ECU) to control them,
- a mechanical power splitter that acts as a second differential, called the hybrid transaxle, and
- a NiMH-Battery pack that stores the energy.

Subsection 3.1.1 supplies background information about the functionality of the HSD. In the second subsection the hybrid vehicle control system is introduced.

3.1.1 Functionality

A continuously variable transmission is the main part of the HSD [5]. A simplified cross section of the hybrid transaxle, the mechanical gearing design of the system, is displayed in Figure 3.3. This design allows the mechanical power from the ICE to be split three ways:

- extra torque at the wheels (under constant rotation speed),
- extra rotation speed at the wheels (under constant torque),
- and power for an electric generator.

The Hybrid Vehicle Control Unit (HV ECU), which is presented in Subsection 3.1.2, directs the power flow from the engine and motor sources. The hybrid transaxle contains a planetary gear set that adjusts and blends the amount of torque from the ICE and motor-generators as it is needed by the front wheels. MG2 and the ICE work together to drive the wheels. MG2 is mounted on the drive shaft, the annulus, and thus couples torque into or out of the drive shafts. So if electricity is fed into MG2, it adds torque at the wheels. The drive shaft has a second differential: one leg of this differential is attached to the internal combustion engine and the other leg is attached to MG1. The differential relates the rotation speed of the wheels to the rotation speeds of the engine and MG1. MG1 is used to absorb the difference between wheel and engine speed by generating electrical power. This electrical

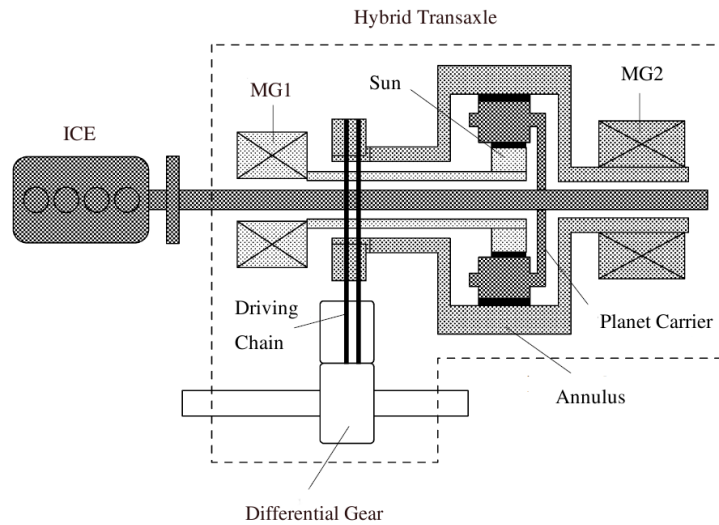


Figure 3.3: Simplified cross section of the hybrid transaxle [6].

power is used for recharging the NiMH-Battery pack. Special couplings and sensors monitor rotation speed of each shaft and the total torque on the drive shafts, for feedback to the control unit.

The HSD works by shunting electrical power between the two motor generators, running off the battery pack, to even out the load on the ICE. Since a power boost from the electrical motors is available for periods of rapid acceleration, the ICE can be down sized to match only the average load on the car. Thus, the smaller internal combustion engine can be designed to run more efficiently. Furthermore, during normal operation the engine can be operated at or near its ideal speed and torque level for power, economy, or emissions, with the battery pack absorbing or supplying power as appropriate to balance the demand placed by the driver. During traffic stops the internal combustion engine can even be turned off for even more economy.

The HSD operates in distinct phases depending on demanded speed and torque. Here, the most important phases of operation are listed:

- Low gear: When accelerating at low speeds in normal operation, the ICE turns more rapidly than the wheels but does not develop sufficient torque. The extra engine speed is fed to MG1. The output of MG1 is fed to MG2, acting as a motor and adding torque at the drive shaft.
- High gear: When cruising at high speed, the engine turns more slowly than the wheels but develops more torque than needed. MG2 then runs as a generator to remove the excess engine torque, producing power that is fed to MG1 acting as a motor to increase the wheel speed. In steady state, the engine provides all of the power to propel the car. During heavy acceleration or driving up a steep incline at high speed the ICE is unable to supply enough power. In this case, the battery supplies the difference.
- Reverse gear: There is no reverse gear as in a conventional gearbox. The HV ECU just feeds negative voltage to MG2, applying negative torque to the wheels. If the battery is low, the system can simultaneously run the engine and draw power from MG1.

- Silent operation: At slow speeds and moderate torques the HSD can drive without running the internal combustion engine at all. Electricity is supplied only to MG2, allowing MG1 to rotate freely (and thus decoupling the engine from the wheels). This is popularly known as *Stealth Mode*. Provided that there is enough battery power, the car can be driven in this silent mode for some miles even without gasoline.
- Regenerative braking: During braking the motor-generators are working in the generator mode converting much of the forward motion into electrical current flow which is used to recharge the batteries while slowing down the vehicle. Harder braking action engages standard front disk and rear drum brakes which are also provided for faster stops and emergency use.

3.1.2 Hybrid Vehicle Control System

The Hybrid Vehicle Control Unit (HV ECU) optimizes the power output and the torque of driving forces to reduce the fuel consumption and the pollutant of the exhaust gas [6]. The optimal required driving power of the ICE, MG1 and MG2 is based on its inputs signals which are the gas pedal position, rotation speed of the drive shaft and gear shift lever position. Also the state of charge (SOC) of the battery pack and the temperature of the motor-generators have influence on the optimal driving power. Figure 3.4 shows a schematic diagram of the communication between the HV ECU and the other HSD devices.

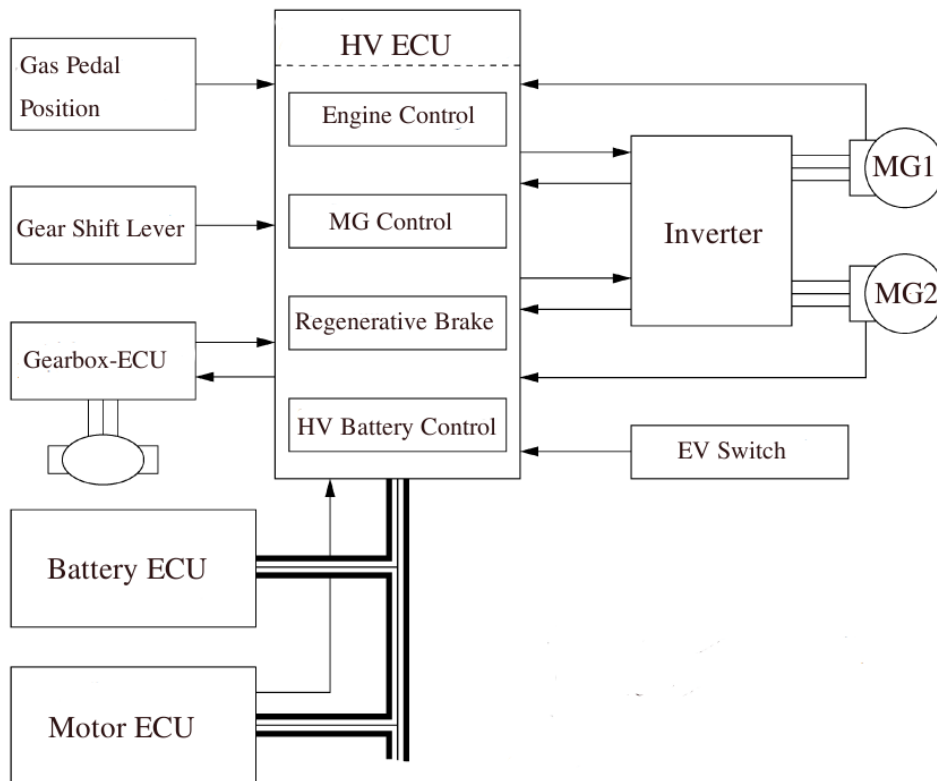


Figure 3.4: Diagram of the HSD communication system [6].

3.2 Controller Area Network

Based on sensor data inputs Electronic Control Units (ECUs) control different actuators [7]. The ECUs, sensors and actuators communicate with each other through so-called multiplex-communication systems. The Prius uses primarily three different communication systems:

- Controller Area Network (CAN)
- Body Electronics Area Network (BEAN)
- Audio Visual Communication-Local Area Network (AVC-LAN)

The following subsection gives an overview of the three communications systems of the Prius. Subsection 3.2.2 introduces the CAN. The last subsection shows the usage of the CAN bus in the Toyota Prius.

3.2.1 Multiplex-Communication Systems

Multiplex-communication systems (MPXs) uses serial communication between the connected ECUs [8]. Compared to parallel communication systems, where every subsystems is connected separately with the other subsystems, serial communication systems connects all ECUs through one single channel called bus. For data transfer through these buses the information has to be converted into data frames. Table 3.1

MPX	Connected devices	Maximum communication speed [<i>kbit/s</i>]	Data length [<i>bytes</i>]
CAN	EV Battery Chassis Motor Braking Anti-lock Breaking System (ABS) Steering Angle Sensor Inertial Measurement Units (IMU) Electric Power Steering (EPS) Hybrid Vehicle Control System (HV)	1000	0–8
BEAN	Gearbox Control Autobody (Windows, Lightning...) Operating System Air Conditioning System Smartkey Car-theft Protection	10	0–11
AVC-LAN	Multidisplay Navigation Hi-Fi System	17.8	0–32

Table 3.1: Properties of the Prius MPXs [6].

gives an overview of the properties of the MPXs and which components of the Prius they connect together. The networks are working on the same concept, but they have different message formats, message lengths and communications speeds.

The BEAN is also called comfort bus. It contains control devices as for lightning, windows and air conditioning system. Hence, no high communication speed is

required. Operation, display and navigation systems are connected through the AVC-LAN. The CAN is responsible for the communication between the ICE and the HSD system. This network allows a fast and secure data transfer. The three MPXs are connected through the Gateway-ECU which allows a coupling of networks with different architectures.

3.2.2 CAN Protocol

The Controller Area Network (CAN) was developed by the ROBERT BOSCH GmbH [8]. Originally, it was used as a standard bus system for automobiles. Today, it is also used in other areas such as automation systems. The CAN is a multi-master network which uses serial communication. Thus, every member of the network has equal and active access to the bus, means that every member is allowed to receive and send onto the CAN bus. The CAN bases on a protocol that supports real-time data communication between control devices that guarantees a high level of safety. Incomplete or incorrect messages are re-transmitted automatically.

A simple example of a CAN where three ECUs are connected trough a CAN bus is depicted in Fiure 3.5. Each member of the CAN, called node, is able to send messages (also known as frames) onto the CAN bus, but not simultaneously. The message is transmitted serially on the bus and is sensed by all other nodes. If the bus is free (no node is sending a message), any node may begin to transmit a message. If two or more nodes begin sending at the same time, the message with the more dominant Identifier (ID), means lower ID value, will overwrite the other messages. Messages with a high ID value will be sent later when the bus is free.

Bit rates up to 1 *Mbit/s* are possible in a network with a length below 40 *m*. Longer network distances decreases the bit rate.

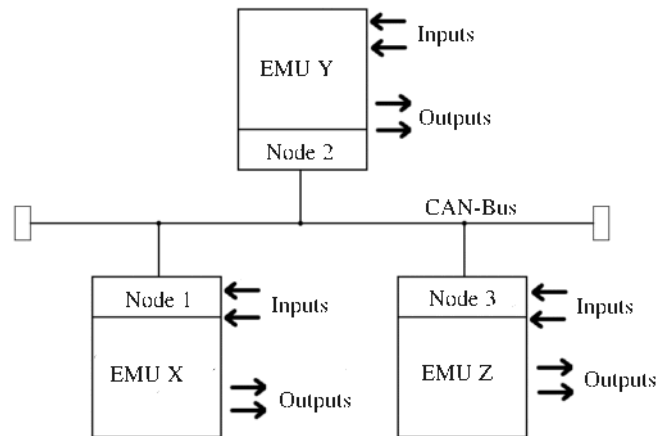


Figure 3.5: Diagram of a CAN with three members [8].

Nodes

Each node consists of a host processor, a CAN controller and a Transceiver [9]. The host processor reads messages and decide which message it want to transmit itself. The CAN controller receives messages by storing the bits and sends the entire message to the host computer or transmits bits serially on the bus if the host processor wants send a message. The transceiver adapts signal levels from the bus (receiving)

or converts the transmit-bit signal received from the CAN controller into a signal that is sent onto the bus (sending).

Frames

Each frame is a sequence of bits which are serial transferred by the CAN bus. The CAN can be configured to work with two different frame formats: the *standard frame format* and the *extended frame format* [9]. The two format differs only in their length of bits of the identifier (ID). The *standard frame format*, which is used in the CAN bus of the Prius, supports a length of 11 bits and the *extended frame format* supports a length of 29 bits.

In this section, only the *standard frame format* will be considered. The CAN protocol distinguish between four types of frame types:

- Data frame: contains node data for transmission.
- Remote frame: requests the transmission of a specific identifier.
- Error frame: transmitted by any node that detects an error.
- Overload frame: injects a delay between data and/or remote frames.

The *standard frame format* is described in Table 3.2. The most important fields of CAN frames are the identifier and the data field. The CAN protocol uses a object-oriented addressing [8]. Thus, a transmitted message gets a network-defined ID as its address. The nodes listens only for messages with a certain ID. The data field contains the real information of the message.

Filed name	Length [bits]	Purpose
Start-of-frame	1	Denotes the start of frame transmission
Identifier (ID)	11	Unique identifier for the data
Remote transmission request	1	Dominant (0) if specific data frame is requested. See remote frame
Identifier extension bit	1	Dominant (0)
Reserved bit	1	Dominant (0)
Data length code	4	Number of bytes of data (0-8 bytes)
Data field	0-8 [bytes]	Data to be transmitted
CRC	15	Cyclic Redundancy Check
CRC delimiter	1	Must be recessive (1)
ACK slot	1	Transmitter sends recessive (1) and any receiver can assert a dominant (0)
ACK delimiter	1	Must be recessive (1)
End of frame	7	Denotes the end of frame transmission (must be recessive (1))

Table 3.2: Base frame format [9].

3.3 CAN in the Prius

As listed in Table 3.1 and shown in Figure 3.6 the Prius uses the CAN bus to transmit informations between the battery, brake systems, steering angle sensor, EPS (connection assembly 1), ICE control system, IMU and the hybrid control unit

(HV) (connection assembly 2). The location of the CAN devices are shown in Figure 3.7.

The ECUs of the Prius connected to the CAN bus do not use remote frames [11]. Therefore, all messages are sent periodically or event-oriented. The DLC3 port is

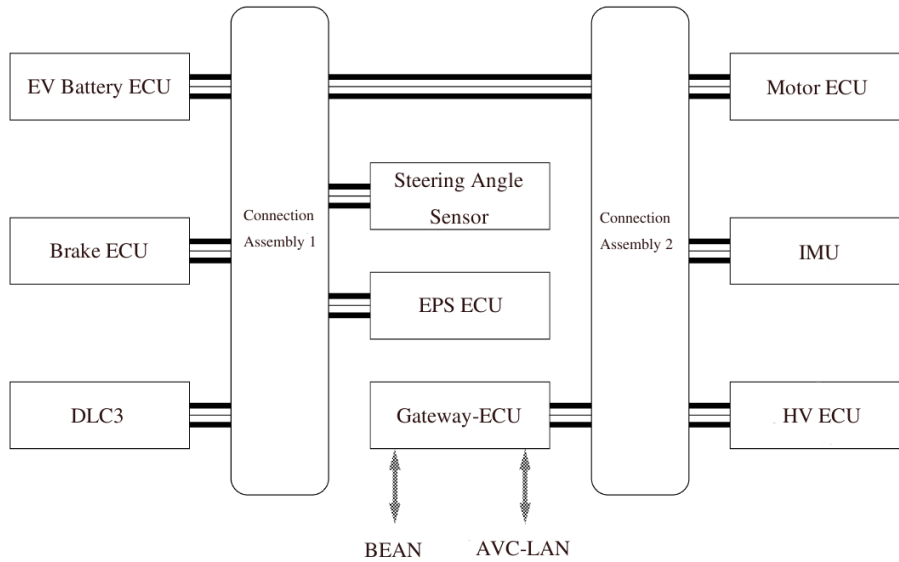


Figure 3.6: Schema of the Prius CAN bus. [6]

a serial CAN interface and is originally installed for the coupling of diagnostic devices [6]. Diagnostics Trouble Codes (DTCs), which contains detected disturbances in data exchange, are sent by the particular ECU that wants to report the error and are stored by the ECU of the DLC3. With an *Intelligent Tester II* the DTCs can be retrieved. This is usually done by car mechanics.

The described DLC3 connector has a RS232 port [8]. For this project, we were working with RS232 to USB-Converter to get access of the CAN bus. Unfortunately, the RS232 transfer rate is limited to 51.7 *kbit/s*.

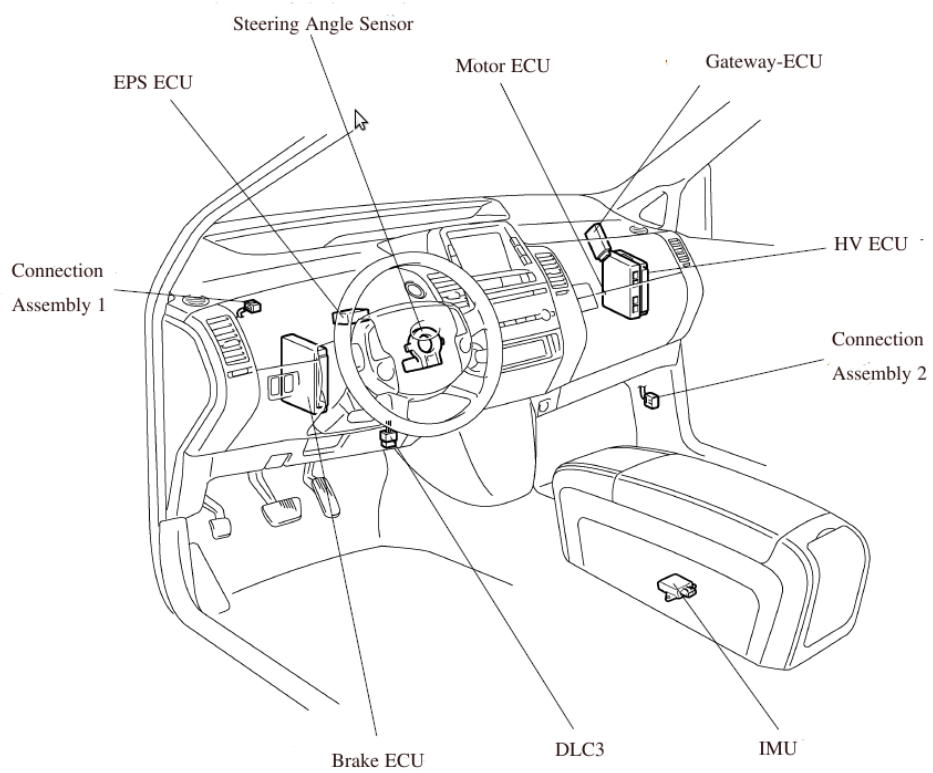


Figure 3.7: Location of CAN components. [6]

Chapter 4

Methodology

There were three main tasks in this project. First we had to connect the laptop to the CAN bus, that is described in Section 4.1. In Section 4.2 is explained how we analysed the CAN messages, identified their content and display the desired states of the Prius. The last task was to modify some CAN messages and send them over the CAN bus to control actuators. The results are shown in Chapter 5.

4.1 Connection to the CAN

In a first step we had to connect our laptop to the CAN bus of the Prius. For this we used a CPC-USB device from EMS Dr. Thomas Wuensche. This device, shown



Figure 4.1: CPC-USB device.

in Figure 4.1, has on one side an USB-adapter to link with a PC and a RS232-port which we connected to the On-Board Diagnostics (ODB) adapter. Figure 4.2 illustrates how we connected the laptop to the CPC-device (red circle) and then to the diagnosis adapter (green circle). Afterwards we adapted the CAN driver from another ASL project to our problem. So after some experiments, we were able to receive CAN messages. In the next step we analyzed the CAN messages.

4.2 Messages Analysis

First we wanted to find out how many different CAN IDs existed, so we could compare the IDs that we received with the list of Vass [2]. It was also of interest to get the length of the content, i.e. number of bytes, and the frequency of every

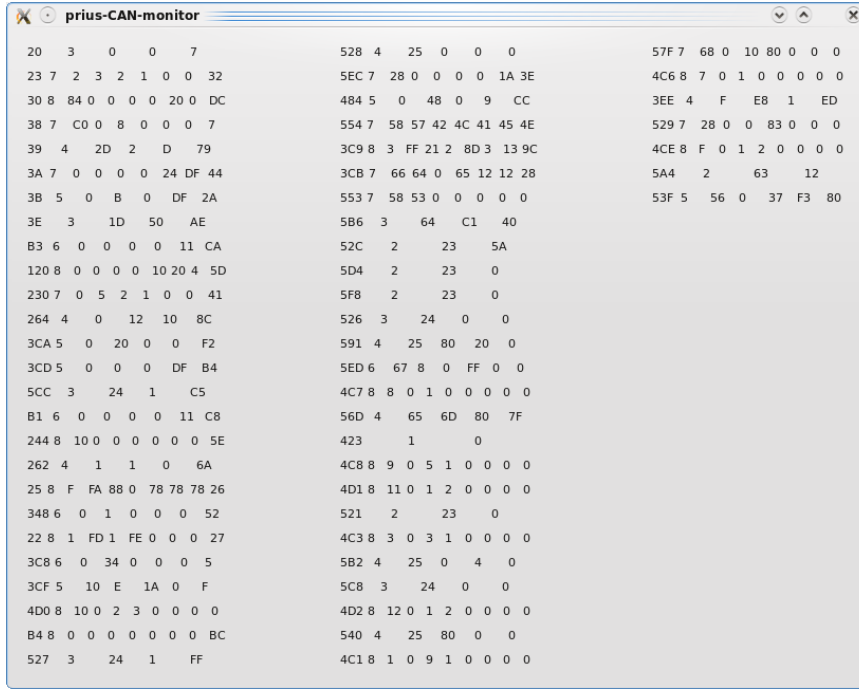


Figure 4.2: Connection between laptop and DLC3 port.

CAN ID with which we received them. So we wrote a program that stored all CAN IDs and their length and calculated their sample frequencies. The frequency was calculated in two different ways. On the one hand the program measured the time to receive 500'000 CAN messages and then counted the number of received messages with the same ID. In a second approach the program measured the time between two CAN messages with the same ID. We observed that the elapsed time was not constant. All the measured times between two CAN messages with the same identifier were multiples of the smallest value. So the frequency with which CAN messages were sent was not equal to the frequency with which we received them. This was because of limited transfer rate of the DLC3 connector.

The next task was to understand the content of the CAN messages. We had a small monitoring tool that displayed all the different CAN IDs with their length and the content of the last message that was received. An example of this tool is shown in Figure 4.3. With the information we got from Vass [2] we already had guesses about the content of the messages. For a first approach, we choosed ten different states that we wanted to display on a GUI. The decision which states should be observed was influenced by three factors. For the reverse engineering it was necessary to understand the messages of the states, that we wanted to control, like steering angle, gear, brake and gas pedal position. We also displayed states that easily could be checked if we write succesfully to the CAN bus, e.g. headlamp. Third aspect was to display states that are interesting for feedback control, e.g. velocity and engine speed.

In the following is explained how we confirmed the information from the literature und computed the scaling coefficient by the example of the steering angle. From the literature we expected that only the content of the message with the ID $0x25$ will change. After starting the monitoring tool we turned the steering wheel. We observed that the content of three messages changed, namely the CAN IDs $0x25$, $0x262$ and $0x264$. We concentrated first on the CAN message with the ID $0x25$. While turning the steering wheel counterclockwise the second byte of the data field increased to $0xFF$, then it jumped back to $0x00$ and the first byte increased from $0x00$ to $0x01$. So the first two bytes of the ID $0x25$ represented the angle of the



```

prius-CAN-monitor
20 3 0 0 7          528 4 25 0 0 0    57F 7 68 0 10 80 0 0 0
23 7 2 3 2 1 0 0 32 5EC 7 28 0 0 0 0 1A 3E 4C6 8 7 0 1 0 0 0 0 0
30 8 84 0 0 0 0 20 0 DC 484 5 0 48 0 9 CC 3EE 4 F E8 1 ED
38 7 C0 0 8 0 0 0 7 554 7 58 57 42 4C 41 45 4E 529 7 28 0 0 83 0 0 0
39 4 2D 2 D 79      3C9 8 3 FF 21 2 8D 3 13 9C 4CE 8 F 0 1 2 0 0 0 0
3A 7 0 0 0 0 24 DF 44 3CB 7 66 64 0 65 12 12 28 5A4 2 63 12
3B 5 0 B 0 DF 2A    553 7 58 53 0 0 0 0 0 53F 5 56 0 37 F3 80
3E 3 1D 50 AE       5B6 3 64 C1 40
B3 6 0 0 0 0 11 CA  52C 2 23 5A
120 8 0 0 0 0 10 20 4 5D 5D4 2 23 0
230 7 0 5 2 1 0 0 41 5F8 2 23 0
264 4 0 12 10 8C    526 3 24 0 0
3CA 5 0 20 0 0 F2   591 4 25 80 20 0
3CD 5 0 0 0 DF B4   5ED 6 67 8 0 FF 0 0
5CC 3 24 1 C5       4C7 8 8 0 1 0 0 0 0 0
B1 6 0 0 0 11 C8    56D 4 65 6D 80 7F
244 8 10 0 0 0 0 5E 423 1 0
262 4 1 1 0 6A      4C8 8 9 0 5 1 0 0 0 0
25 8 F FA 88 0 78 78 26 4D1 8 11 0 1 2 0 0 0 0
348 6 0 1 0 0 52    521 2 23 0
22 8 1 FD 1 FE 0 0 27 4C3 8 3 0 3 1 0 0 0 0
3C8 6 0 34 0 0 5    5B2 4 25 0 4 0
3CF 5 10 E 1A 0 F   5C8 3 24 0 0
4D0 8 10 0 2 3 0 0 0 4D2 8 12 0 1 2 0 0 0 0
B4 8 0 0 0 0 0 0 BC 540 4 25 80 0 0
527 3 24 1 FF       4C1 8 1 0 9 1 0 0 0 0

```

Figure 4.3: Example of the monitoring tool.

steering wheel. If we rotated counterclockwise by one revolution the second byte increased by $0xF0$, that means that we have a resolution of $\frac{360^\circ}{240} = 1.5^\circ$. When we turned the steering wheel clockwise the value of the second byte decreased and when the first and the second bytes were $0x00$ the first jumped to $0x0F$ and the second jumped to $0xFF$. That means that if the value is larger than 2048 the steering angle is negative. The last parameter that we had to define was the offset δ from the zero-position. We defined that at if the steering wheel is at the zero-position, the front wheel are in a line with the rear wheel, so the car goes straight on. δ can be positive or negative. The formula to compute the steering angle ϕ from the first two bytes from the CAN message with the ID $0x25$ looks as follows:

$$\phi = \begin{cases} (b_0 \cdot 16^2 + b_1 - \delta) \cdot \frac{360}{240} & \text{if } b_0 \cdot 16^2 + b_1 - \delta < 2048 \\ (b_0 \cdot 16^2 + b_1 - \delta - 4096) \cdot \frac{360}{240} & \text{if } b_0 \cdot 16^2 + b_1 - \delta \geq 2048 \end{cases} \quad (4.1)$$

Here b_0 and b_1 are the values of the first two bytes. We found out that the content of the CAN ID $0x264$ behaves similar, except that the offset value δ is different. That would be enough if we just wanted to read out the states of the Prius. Since we also want to change the states of the car we had to figure out what the other bytes of the data field represent, because we had to be able to duplicate the whole message. But before, we wanted to make sure that we can read out every state and display them, so we continued with the other states. How we figured out what the other bytes represent is described in Section 4.3. The steering angle was easy to discover, because the real value of the state was easy to determine. But for other states, e.g. the acceleration sensors or the engine temperature, it is very difficult to get the real values.

In the last step we wanted to display the values of the desired states in a GUI. We did this by opening a second thread. One is continuously checking the incoming CAN message if it contains useful informations, if so it stores it. The other thread

takes the values from the storage and display them in a GUI. The GUI is shown in Figure 5.1.

4.3 Control Actuators

First we had to figure out what is really controllable through the CAN bus. Since the Prius has an Intelligent Parking Assist System (IPAS), we wanted to check if this controls the steering wheel through the CAN bus. We had a program that logged every CAN message that we received and the time when it was received. Afterwards, a second program sent the logged data in the same order and with the same timestamps to the CAN bus. In a first attempt, we maneuvered the Prius and logged all CAN messages and afterwards duplicate this event, but we could not observe any reaction of the Prius. In a second attempt we were logging the data during IPAS supported parking. In a further step we sent the logged messages back onto the CAN bus. We noticed that the steering wheel and the display of the gear reacted to the sent messages. So we compared the received messages during driving the car in normal mode and in IPAS aided mode. With the monitoring tool we observed all the CAN messages and, by switching between IPAS and normal mode, saw that some content of the CAN message with the identifiers $0x262$ and $0x264$ have changed. So the next step was to figure out what every byte of the content of this CAN messages represent. We started with the message of the identifier $0x264$. As described in Section 4.2, the content of this message tells us something about the steering wheel. The first two bytes of the data field represent the steering angle. The third byte changes from $0x10$ to $0x30$ if we activate the IPAS. The last byte was a checksum, to verify that there was no transition error in the CAN bus. The checksum looks like this:

$$b_3 = (0x2 + 0x64 + 0x4 + b_0 + b_1 + b_2) \pmod{256} \quad (4.2)$$

where $0x2$ is the value of the first three bits and $0x64$ is the value of the last eight bits of the identifier. $0x4$ is the length of the data field and b_0 , b_1 , b_2 and b_3 are the values of the four bytes of the content. The equation 4.2 means that the last byte is build with the sum of the two bytes from the identifier, the length of the message and the first three bytes of the content. This checksum is used often in the CAN of the Prius. The content of the message with the identifier $0x262$ represents the torque on the steering column. If we applied a low torque to the steering wheel the value of the second byte jumped from $0x01$ to $0x03$. When we increased the torque the value of the first byte switched from $0x01$ to $0x0D$. The values looked the same if we turned the steering wheel to the clockwise or counterclockwise, so there is no information about the direction. If we activated the IPAS the values of the first two bytes jumped to $0x03$. The third byte has always the value $0x00$ and the last byte is again a checksum. So we were able to create the two CAN messages which are responsible for steering during IPAS aided parking. The IPAS operates only in the reverse gear, so if the gearshift is not in reverse nothing happens. But we did not care about that in the beginning and concentrate on turning the steering wheel to a desired angle.

First we sent only the CAN message with the ID $0x264$ that contained a target angle of the steering wheel to the CAN and observed that the servo tried to fit the real steering angle to the target angle, but with a bad behavior. By additional sending the CAN message with the ID $0x262$ and changing the values of the first two data bytes, we could improve its behavior. It turned out that the best values for this parameters are $0x03$ and $0x03$, like they are if IPAS is activated. But it was still not good enough to steer the car. The next attempt was to change our sending

frequency. We observed that the behavior was getting better if we increased the frequency. For a short amount of time it looked good, but then the servo seemed to be disturbed, or receiving no informations, so it stopped turning. After some time, mostly about two seconds, the ECU tried again to reach the target angle for a short amount of time, and then stopped again. We wanted to figure out why the steering wheel tried to turn to the angle that was stored in $0x264$, so we used a tool that plots the values of the first two bytes of the CAN messages with the ID $0x25$ and $0x264$ while driving in normal mode and driving with the activated IPAS. An

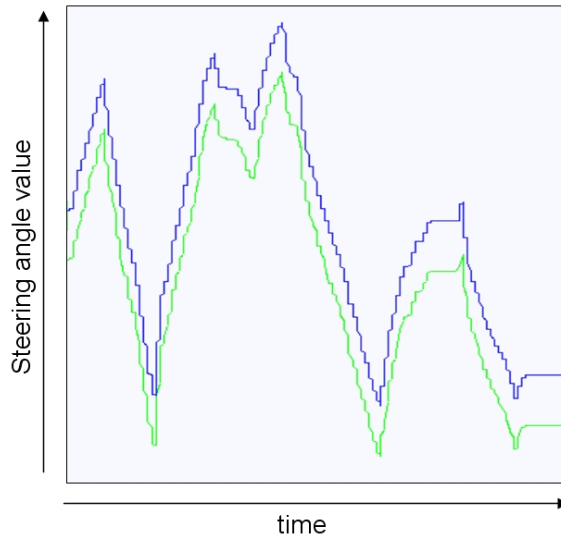


Figure 4.4: Course of the steering angle value of $0x25$ (green) and $0x264$ (blue).

example of the courses is shown in Figure 4.4 where the blue line represents the progress of the steering angle that is stored in the content of the ID $0x264$. The green line shows the progress of the steering angle that is stored in the content of the ID $0x25$. We observed that there were no differences between the driving modes, so we could not go further in this direction. Our next step was to send also the message with the CAN ID $0x25$ to see how the behaviour of the steering wheel will change. Obviously we first had to figure out, what information is stored in every byte. Like described earlier, the first two bytes represents the angle of the steering wheel. We observed, that the third byte was always $0x88$ and the fourth always $0x00$. The fifth and sixth byte depended on the angular velocity of the steering wheel, but are quite hard to interpret more accurate and the seventh byte was always around $0x79$. Like most of the messages, the last byte is a checksum. So we were able to create this three messages and sent them onto the CAN bus. But the problem was, that now the ECU did not know anymore what the real value of the steering angle was. So the behavior of the steering wheel could not be improved with this.

In parallel we tried to solve the problem, that we could only change the steering angle if the gear was in reverse. We found two CAN IDs which represents the gear, namely $0x120$ and $0x540$. Since the sample frequency of $0x120$ is much higher we sended this message, where we modified the content in the way that the IPAS reads out, that the gearshift was in reverse. With this approach we could turn the steering wheel, even if we were driving forward. But since we sent always three CAN messages at the same time and the transfer rate of the DLC3 adapter is limited, the behavior of the steering wheel was bad.

Chapter 5

Results

In this chapter we show the results of what we achieved during the project. It is structured as follows. In Section 5.1 we illustrate the results of the analysis of the CAN messages and in Section 5.2 we show the results of modifying CAN messages to control actuators through the CAN bus.

5.1 Results of Messages Analysis

To get the states of the Prius from the CAN bus we wrote a library that contains functions to open the CAN bus, receive CAN messages, identify their contents, convert the important bytes to get the values of the states and store them in a state-structure. The states are shown in Table 5.1. We defined the steering angle,

ID	Information	Unit	Receiving Freq. [Hz]	Minimum Timestamp [ms]
0x30	Brake Pedal Position	[%]	31.7	6
0x120	Gear	['P', 'R', 'D', 'N', 'B']	39.3	16
0x244	Gas Pedal Position	[%]	25	24
0x264	Steering Angle	[-]	24.7	20
0x3C8	Engine Speed	[RPM]	9.2	65
0x3CA	Velocity	$[\frac{km}{h}]$	6.7	100
0x3CB	SOC Hybrid Battery	[%]	6.1	100
0x57F	Headlamp	['O', 'P', 'N', 'H']	0.6	1000
0x5A4	Tank Level	[%]	0.2	3200
0x5B6	Open Doors	[-]	0.6	1000

Table 5.1: ID and content of CAN messages.

like the value in the CAN message, as positive, if we turn the steering wheel to the left, so counterclockwise, and negative if we turn clockwise. The states of the brake pedal, the gas pedal, the SOC of the hybrid battery and the tank level are stored in %, so their values has to be between 0 and 100. The headlamp has only four possible states and is stored as 'O' (off), 'P' (park), 'N' (normal) or 'H' (high beam). It is also possible to detect if the door of the driver, the door of the passenger and/or one in the back is open. That is why the state of the doors is stored as a struct with three booleans. There are much more information in the CAN messages, but there are all straight forward to store. For clarity of the GUI, we decided to display

only this ten states. The GUI for displaying the states is shown in Figure 5.1. A major drawback of reading CAN messages for displaying states is that the fre-

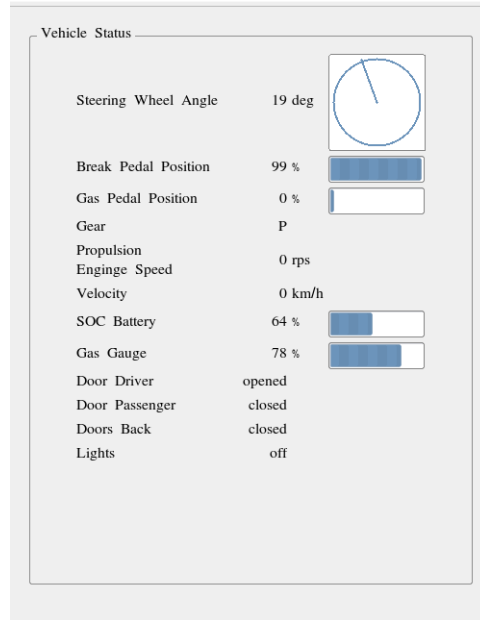


Figure 5.1: GUI displaying several states of the Prius.

quencies are not constant. That could lead to problems if a certain state will be controlled by using a feedback-loop. The reasons for inconstant frequencies is the low transfer rate of the DLC3-Connector (see Section 3.3) and the priority system of the CAN bus.

5.2 Results of Control Actuators

As discribed in Section 4.2, it is possible to send messages through the CAN bus, but it is hard to control existing nodes. At the beginning of the project the goal was to control the steering angle, the gas pedal, the break pedal and the gear. A big problem to control actuators through the CAN bus is that the sensor, which measures the driver input and the actuator, that controls the output, are both directly connected to the same ECU. In Figure 5.2 is shown, that the torque sensor of the steering wheel and the power steering electric motor are both directly connected to the Electronic Power Steering (EPS) ECU. The same problem occurs with the gear as can be seen in Figure 5.3. There the gearshift sends its state to the HV ECU, that sends the state through the CAN bus and directly to the Gearbox ECU, which controls the gear.

So if this is the case, it seems not possible to control the actuators without a modification of the CAN bus. There is still a possibility that another ECU has an influence of the behavior of a state, or is even able to control it. But to find out which ECU can change the state is not possible without any information from the producer.

In some cases the sensor and the actuator are linked to different ECUs, which are connected together over the CAN bus. For example during cruise mode, the gaspedal sensor is linked to the HV ECU, that computes a torque demand and sends this through the CAN bus to the engine control unit, which controls the throttle

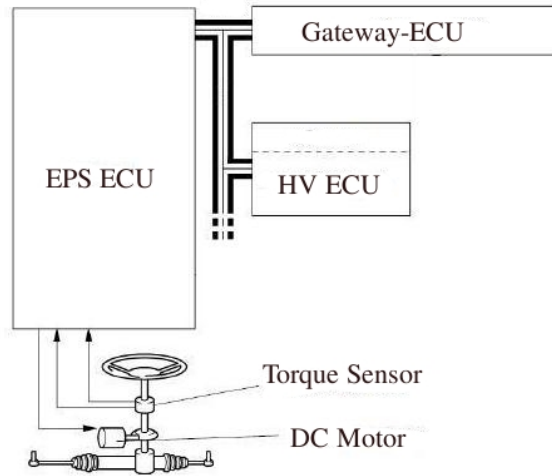


Figure 5.2: CAN diagram of EPS.

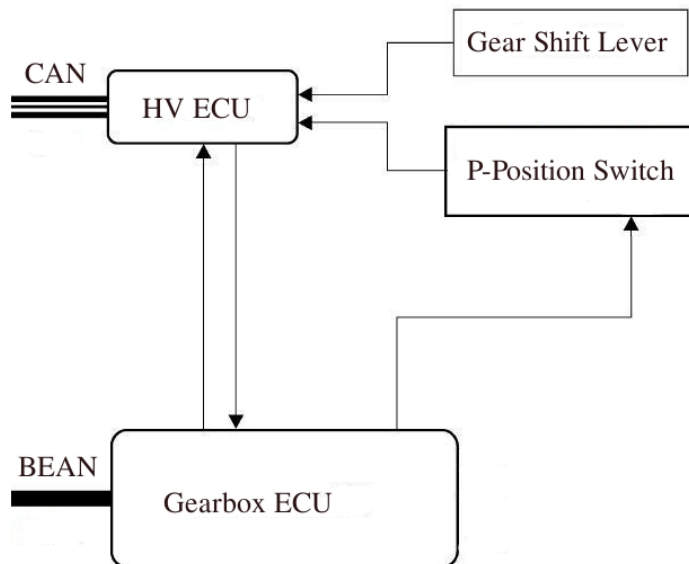


Figure 5.3: CAN diagram of the gearshift.

valve. This is shown in Figure 5.4. It looks like it is possible to control the throttle valve through the CAN bus, but this works only for the internal combustion engine. Since it is not possible to control the motor-generators, we have to make sure that these are disabled. Analog to the gaspedal is the regenerative part of the brake controlled through the CAN bus. This sounds nice, but the problem is, that we have to be able to generate exactly the necessary CAN message. Even if we could create and send this message, the real message will still be sent and the ECU of the actuator receives two different messages.

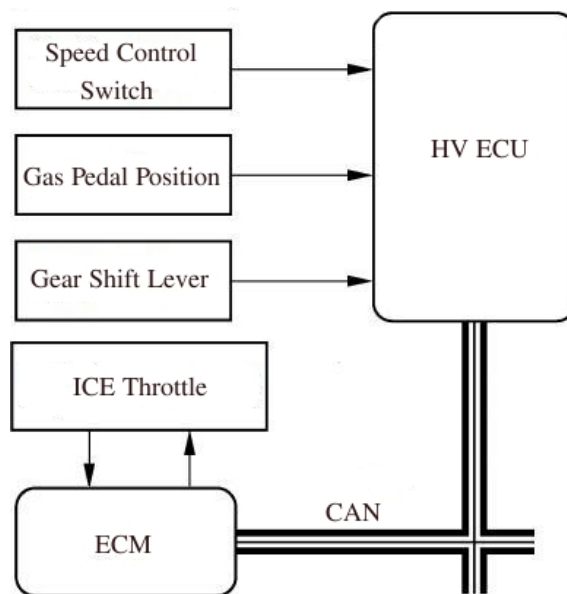


Figure 5.4: CAN diagram of the signal from the gas pedal to the throttle valve.

Chapter 6

Conclusion and Further Work

There were two main goals for this project, namely to display different states in GUI and to control some actuators without modifying the CAN bus. We saw that there are a lot of informations in the CAN messages. The hard part of reading out desired states was to find out, which byte of which message represents the required informations. Once we knew that, it was straight forward to transform the bytes to desired values. If we want to use the states for a feedback control we have the problem, that the sample frequencies of the states are not constant and can be low. This is because we loose messages since the transfer rate of the DLC3 port is limited. If we would add a new ECU as a node to the CAN bus, the limitation of the transfer rate could be avoided, but this has to be tested.

It was much harder to fulfill the control task. As described in Section 5.2 it is possible to send messages through the CAN bus, but there are some problems to control existing nodes. One problem is that some actuators are not controlled through the CAN bus. That means the sensors and the actuators are directly connected to the corresponding ECU, which controls the state. This is the case for the steering wheel (see Figure 5.2), and the Gear (see Figure 5.3). A second problem is that even if an ECU, that controls an actuator, considers CAN messages from other ECUs and we are able to create and send this messages, the controlling ECU receives both, the original and the faked message. This is the case for the throttle valve as you can see Figure 5.4. These problems can only be solved by modifying the CAN bus or the electric of the Prius. A possible solution could be to change the signals from the sensors or to the actuators electronically without using the CAN bus or to add electrical switches to neglect the original signals. Another approach is to reprogram the ECU in such a way that it considers also some new CAN messages for the output. The drawback is, that it could be dangerous to modify working ECUs that controls the steering angle or the throttle valve, because if they are not fully reliable anymore the car could get out of control.

But even with this solutions it is not guaranteed to control every state. A simple solution is to add ECUs to the CAN bus as new nodes. This ECUs could be able modify sensor signals and/or control actuators. This solution has the advantage that it is not necessary to reprogram the existing ECUs, so safety is guaranteed by human intervention.

Bibliography

- [1] P. LAMON, S. KOLSKI, R. SIEGWART: *The SmartTer - a Vehicle for Fully Autonomous Navigation and Mapping in Outdoor Environments*. Swiss Federal Institute of Technology Zurich, Autonomous Systems Lab (ASL).
- [2] A. VASS: *My CAN Project*.
<http://www.vassfamily.net>
- [3] *The Team Lux*.
<http://www.team-lux.com>
- [4] TOYOTA MOTOR CORPORATION (TMC): *Worldwide Prius Sales Top 1 Million Mark*. Japan, May, 15, 2008.
<http://www.toyota.co.jp/en/news/08/0515.html>
- [5] WIKIPEDIA: *Hybrid Synergy Drive*.
http://en.wikipedia.org/wiki/Hybrid_Synergy_Drive
- [6] TOYOTA MOTOR CORPORATION (TMC) *Manual, Prius NHW20*.
- [7] WIKIPEDIA: *Electrical Control Unit*.
http://en.wikipedia.org/wiki/Electronic_control_unit
- [8] H. ENGELS: *CAN-BUS*. In Franzis Verlag GmbH, Second Edition, 2002, Pages 49-118.
- [9] WIKIPEDIA: *Controller Area Network*.
http://en.wikipedia.org/wiki/Controller_area_network
- [10] TOYOTA MOTOR CORPORATION (TMC): *Toyota Germany*.
<http://www.toyota.de>
- [11] *Prius PHEV TechInfo*.
http://www.eaa-phev.org/wiki/Prius_PHEV_TechInfo