Electronic Breakout Unit

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This thesis studies the problem to measure and control signals on a Volvo L110G wheel loader without interfering with the original Electronic Control Units. The aim is to develop an Electronic Breakout Unit (EBU) that can be connected to the original wiring without damaging or altering any of the original electronics. The EBU shall be controlled over Ethernet. This allows for data to be logged by an on-board PC while the wheel loader is tested on the field. The on-board PC also allows the wheel loader to be controlled with advanced remote control algorithms. In this work, the hardware design considerations of a concept to measure and control a vehicle through an electronic add-on system is presented. Future work for the system is to test and develop software so the wheel loader can be controlled by an on-board PC.
First of all, I would like to express my gratitude to my supervisor at LTU, Håkan Fredriksson and to my external supervisor at Volvo Construction Equipment, Jonatan Blom. For their guidance and support. I would also like to thank Anton Videnius how helped me with brainstorming and the layout of the Ethernet module.

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Fredrik Häggström
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In this work, the considerations of designing hardware to measure and control a vehicle through an electronic add-on system is presented. The add-on system should not take up any space from the driver in the driver’s compartment and all electrical wiring should be kept intact.

Such a system can be used to log data during tests on the field to find problems in the vehicle’s control loops that can’t be found in the test-bench. Alternatively, it can be used to control the vehicle remotely or autonomously, which can improve the security for personnel that work in a hazardous environment. Volvo Construction Equipment has lent a wheel loader to Luleå University of Technology as a test platform, seen in Figure 1.1.

Figure 1.1: Volvo L110G wheel loader.
1.1 Background

The department of Computer Science, Electrical and Space Engineering at Luleå University of Technology (LTU) is collaborating with Volvo Construction Equipment (VCE) in projects regarding driver assistance systems and unmanned vehicles. The focus of this master thesis is directed towards Volvos L110G wheel loader. Both VCE and LTU want to be able to log and interact with the signals on the wheel loader to test and develop new algorithms and features.

There are other systems on the market that can monitor and control the wheel loader. However they are bulky, expensive and needs to be patched in to the original wiring that will damage the original wiring harness. VCE have done some testing with such systems but are not satisfied with their interface and that they have to damage the wiring on the vehicle [1, 2, 3, 4].

1.2 Problem

VCE requested a system that could log most of the signals on the Electronic Control Units on the wheel loader at a rate of at least $50\, \text{Hz}$. It should be able to take over signals and control sub systems of the wheel loader. It should not take up any space from the driver in the driver compartment and it shold be easy to install without damaging the original wiring harness. See Appendix A for the requirements specification.
1.3 System

The box named EBU in Figure 1.2 is the Electronic Breakout Unit that this thesis is focused upon. It should be able to log all signals that is going in and out of the ECU and transmit them via Ethernet to an on-board computer (L110G-PC). The EBU should also be able take over part of the signals without disturbing the original ECUs.

The on-board computer (L110G-PC) has both connection with the Electronic Breakout Units (EBUs) and the outside world via Wi-Fi. This enables the wheel loader to be controlled by some external source or to let the on-board computer directly control the wheel loader. Extra sensors can be connected to the on-board computer if needed.

The layout of the system was given at the start of this project and is not part of the thesis. Several other student projects are running in parallel with this thesis, where all the projects are focused upon extending the wheel loader's awareness to its surrounding environment and controlling the wheel loader.

Figure 1.2: System overview.
## 1.4 Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>CLK</td>
<td>Clock</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal–Oxide–Semiconductor</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>CS</td>
<td>Chip Select</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analog Converter</td>
</tr>
<tr>
<td>EBU</td>
<td>Electronic Breakout Unit</td>
</tr>
<tr>
<td>ECU</td>
<td>Electronic Control Unit (Engine Control Unit)</td>
</tr>
<tr>
<td>EMC</td>
<td>Electromagnetic Compatibility</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>LED</td>
<td>Light-Emitting Diode</td>
</tr>
<tr>
<td>LTU</td>
<td>Luleå University of Technology</td>
</tr>
<tr>
<td>MCU</td>
<td>Microcontroller</td>
</tr>
<tr>
<td>MISO</td>
<td>Master Input, Slave Output</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal–Oxide–Semiconductor Field-Effect Transistor</td>
</tr>
<tr>
<td>MOSI</td>
<td>Master Output, Slave Input</td>
</tr>
<tr>
<td>NTC</td>
<td>Negative Temperature Coefficient</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse-Width Modulation</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>SPI</td>
<td>Serial Peripheral Interface Bus</td>
</tr>
<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver Transmitter</td>
</tr>
<tr>
<td>VCE</td>
<td>Volvo Construction Equipment</td>
</tr>
<tr>
<td>VDD</td>
<td>Positive supply voltage</td>
</tr>
</tbody>
</table>

Table 1.1: Acronyms and description.
CHAPTER 2

Material and Method

This chapter presents the wheel loader, its sensors, actuators and communication buses. It also describes how the sensors can be measured and how the actuators can be controlled.

2.1 The Wheel Loader

The L110G is an all-round front end bucket loader that has a wide range of work areas. It can be equipped with several different buckets and attachments that suit the work load. The operating weight is 19840 kg and it can lift around 12000 kg dependent on the attachment[5]. Figure 2.1 show how the wheel loader looks and how its boom and tilt angles can be maneuvered.

The electrical system on the wheel loader runs on two 12 V batteries in series, giving a 24 V supply voltage. The batteries are continuously charged through an alternator when the engine is running. However, when cranking the engine in cold weather the supply voltage can go down to 9 V. That is why all the electrical devices on the wheel loader are specified to operate down to 9 V.

The wheel loader is equipped from factory with sensors and actuators that can monitor and control its movements. It has several Electronic Control Units (ECU) which the sensors and actuators are connected to. The ECUs can monitor and control sensors that are not connected locally by communicating to other ECUs via communication buses. The L110G wheel loader has two CAN buses and one J1708 bus.

2.1.1 Sensors

A control system gathers physical information about the system through sensors. Sensors transform quantities of physical properties to voltages and currents that can be measured in an electrical system. Some sensors have a digital interface that converts the physical property to a digital value. The sensor enables to control processes, give information to
the driver and help the driver. However the sensor data must be trustworthy and be failsafe. If a wire to a sensor disconnects or shorts, it should be detected and the control system should react accordingly.

The wheel loader uses sensors that are designed to give out an analog signal between $0.5 - 4.5V$. If the sensor signal is outside of the approved range it will be regarded as faulty data. If the wire is disconnected or broken the ECU has internal pull-up or pull-down resistors so the signal will go out of the accepted range. This ensures that if a wire to a sensor is damaged, the ECU will detect an error.

**Angle sensor**

Angle sensors are used to measure the angle of the tilt, boom and other links on the wheel loader, and also to get the input from the levers in the driver’s compartment. Volvo uses Hall Effect sensors which are reliable and uses a non-contact technique to measure the angle between two links. Since there is no electrical contact between the links it reduces the wear and tear on the sensor.

Hall Effect sensors measure the absolute magnetic field through the sensor by using the Hall voltage. It is an effect from the Lorenz force, which says that an electron traveling through a magnetic field will have a force acting on it which is perpendicular to both the current and magnetic field [6].

Figure 2.2a shows how the force is applied on an electron which is traveling in a magnetic field. If a free electron enters a magnetic field as Figure 2.2b shows, the force acting on the electron will curve its path.

If the electron is traveling in a conductive material as Figure 2.3 shows, the Lorenz...
Figure 2.2: (a) The force is perpendicular to the velocity and magnetic flux. (b) Free electrons path is curved by the Lorenz force as it enters a magnetic field.

force will push the electrons more to one side of the convective material and create a voltage potential over the two sides.

Figure 2.3: Lorenz force contributing to Hall effect voltage in a conductor.

By subjecting a conductive material to a current and magnetic field which is perpendicular to each other, the voltage across the conductor can be measured and the strength of the magnetic field can be determined. By having two or three Hall Effect sensors perpendicular to each other, the direction of the magnetic field can be determined in two respective three dimensions.

**Pressure sensor**

The wheel loader uses piezoresistive sensors for measuring pressures in its liquids at locations of interest such as the hydraulic pressure in cylinders and the brakes. A piezoresistive material changes its resistance dependent on the strain it is subjected to.

Monocrystalline silicon, the material used for building transistors and semiconductor
circuitry, has a much greater piezoresistive effect on resistance than what a geometrical change has. This property is used to integrate the sensing element on the same silicon chip as the amplification and temperature compensation circuitry.

The sensing element consists of a thin diaphragm of monocrystalline silicon which have four resistors built on the edges of the diaphragm. Two of the resistors are oriented so they will increase in resistance when a pressure is applied and two is oriented so they will decrease in resistance when pressure is applied.

The four resistive elements are coupled as a Wheatstone bridge and the signal is amplified as in Figure 2.4. The amplified signal is processed to make it linear to the pressure and it is then sent as an analog signal to the control unit.

![Figure 2.4: The Resistive elements is coupled as a Wheatstone bridge and the voltage difference in the legs is amplified.](image)

**Temperature sensor**

The wheel loader uses negative temperature coefficient (NTC) thermistors for measuring temperatures. A thermistor is a resistor which changes its resistance dependent on the temperature it is exposed to. The NTC thermistor gets a lower resistance the higher temperature it has. The relationship between resistance and temperature can be described by Steinhart-Hart equation [7].

\[
\frac{1}{T} = a + b \ln(R) + c \ln^3(R)
\]

Where \(a\), \(b\) and \(c\) are called the Steinhart-Hart parameters and are dependent on which thermistor is used. \(T\) is temperature in kelvin and \(R\) is the resistance in ohms over the thermistor.

One end of the thermistor is often coupled to ground and the other end to a pull up resistor. This will give a voltage potential \(v_t\) over the thermistor that varies with the
temperature as seen in Figure 2.5.

![Thermistor with pull up resistor](image)

Figure 2.5: Thermistor with pull up resistor.

**Inductive sensor**

Inductive sensors are used to measure the velocity of moving parts on the wheel loader. They use the changes in the magnetic flux through the sensor to generate a sinusoidal voltage, where the amplitude and frequency depends on the velocity.

Inductive sensors or commonly known as variable reluctance sensors are composed of a permanent magnet, a ferromagnetic pole piece and a pickup coil. This sensor is then mounted pointing towards a toothed wheel made of a ferromagnetic material as Figure 2.6 shows.

![Inductive sensor and toothed wheel](image)

Figure 2.6: Inductive sensor and toothed wheel.
As the toothed wheel turns, the magnetic flux through the pickup coil changes and generates a voltage which can be described by Faraday’s law of induction.

\[ U(t) = -n \cdot \frac{d\Phi}{dt} \]

Where \( U \) is the generated voltage, \( n \) is number of turns in the pickup coil and \( \Phi \) is the magnetic flux in webers through the pickup coil [6].

By knowing how many teeth the wheel has and the frequency of the signal, the velocity can be calculated. The calculated velocity has to be seen as the absolute velocity, because the rotation direction of the wheel cannot be determined with only one sensor.

### 2.1.2 Actuators

The main actuators on the wheel loader are hydraulic valves which are controlled by solenoids. It has two different types of solenoids, one that only can open fully and one that can open proportionally.

Solenoids are composed of one coil around a movable ferromagnetic armature. The induced force on the armature is proportional to the change in inductance in the coil with respect to the change in position of the armature, and the current flowing through the coil.

The force that is acting on the armature is always in the direction that will increase the induction of the coil. If the armature is asymmetrically placed inside the coil, as in Figure 2.7, the force acting on the armature will strive to center the armature to the coil, because then it has the largest inductance [6].

The armature is connected to the hydraulic valve and as the armature moves, the valve will open and the fluid can pass through it. By controlling the current in the solenoid the force on the valve can be controlled, thus enabling control of flow through the hydraulic valve.

### 2.1.3 Communication

The wheel loader has several ECUs that have to exchange data with each other. It uses two CAN buses and one J1708 bus to connect all the ECUs.

**CAN**

Controller Area Network is a protocol developed by Bosch [8]. It is designed to connect electronic units with a prioritized and robust network which can handle data rates up to 1Mbit/s. There are also sensors that uses CAN to transmit their data and there can be over 100 devices on the same bus. A generic view of a CAN-bus system can be seen in Figure 2.8, it uses 120Ω terminating resistors in each end of the bus to attenuate reflections.
2.1. The Wheel Loader

The physical implementation of CAN is built on an open drain basis with two differential wires, one that is idle high and the other is idle low. If the transceiver sends out a '1' on the bus, it does so by turning off the transistors that is coupled to the wires and letting some internal pull up/down currents go out on the wires and setting them to its idle state. If on the other hand it is going to transmit a '0' the transistors are turned on and the two differential wires are pulled in the other direction. This enables the transmissions to be prioritized without any collisions [9, 10].

The priority of a sent message is based on its ID tag where a lower ID has a higher priority. The ID is the first bits sent after the 'Start-of-frame' bit, see Table 2.1. When the transceiver sends a '1' on the bus it also listens at the same time. If the transceiver detects that another device is sending a dominant '0', it will back off.

If two transceivers start to send a message at the same time they would not notice that another transceiver is sending, until the sent bits differ from each other. For example, consider two transceivers sending at the same time, one sending the ID tag 0x004(0b00000000100) and the other 0x00C(0b00000001100). As long as they are both

![Diagram of a solenoid's internal parts](image)

**Figure 2.7:** A solenoid's internal parts.

![Diagram of a CAN network](image)

**Figure 2.8:** CAN network.
sending '0's the messages are not corrupted or any collisions detected. However when one of the transceivers transmit a '1' and the bus stays at '0', it will notice that someone else is transmitting a '0' and it will back off. This means that the higher prioritized message will succeed and will be transmitted without any collisions.

There are two standards for the CAN frame, the Base frame format and Extended frame format. Since every message on the wires has to have a unique ID tag, the Base format was extended to allow more unique messages to be sent on the bus, see Table 2.1. The data is sent in the Data field and it can vary from 0 to 8 bytes. After that a checksum is sent and the sender listens if any device acknowledged it by answering in the ACK slot [8].

<table>
<thead>
<tr>
<th>Base</th>
<th>bits</th>
<th>Extended</th>
<th>bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-of-frame</td>
<td>1</td>
<td>Start-of-frame</td>
<td>1</td>
</tr>
<tr>
<td>Identifier</td>
<td>11</td>
<td>Identifier A</td>
<td>11</td>
</tr>
<tr>
<td>Remote</td>
<td>1</td>
<td>Substitute remote</td>
<td>1</td>
</tr>
<tr>
<td>transmission</td>
<td></td>
<td>request</td>
<td></td>
</tr>
<tr>
<td>request</td>
<td></td>
<td>Identifier extension bit</td>
<td>1</td>
</tr>
<tr>
<td>Identifier</td>
<td>1</td>
<td>Identifier B</td>
<td>18</td>
</tr>
<tr>
<td>extension bit</td>
<td></td>
<td>Remote transmission request</td>
<td>1</td>
</tr>
<tr>
<td>Reserved bit</td>
<td>1</td>
<td>Reserved bit (r0,</td>
<td>2</td>
</tr>
<tr>
<td>(r0)</td>
<td></td>
<td>r1)</td>
<td></td>
</tr>
<tr>
<td>Data length</td>
<td>4</td>
<td>Data length code</td>
<td>4</td>
</tr>
<tr>
<td>Data field</td>
<td>0-64</td>
<td>Data field</td>
<td>0-64</td>
</tr>
<tr>
<td>CRC</td>
<td>15</td>
<td>CRC</td>
<td>15</td>
</tr>
<tr>
<td>CRC delimiter</td>
<td>1</td>
<td>CRC delimiter</td>
<td>1</td>
</tr>
<tr>
<td>ACK slot</td>
<td>1</td>
<td>ACK slot</td>
<td>1</td>
</tr>
<tr>
<td>ACK delimiter</td>
<td>1</td>
<td>ACK delimiter</td>
<td>1</td>
</tr>
<tr>
<td>End-of-frame</td>
<td>7</td>
<td>End-of-frame</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 2.1: CAN frame.

**J1708**

SAE J1708 is a serial communication standard that is commonly used in heavy vehicles. It is based on normal serial communication with 8 bits, no parity and one stop bit at the rate of 9600 bit/s. The message is composed of up to 21 characters and starts with an ID and finishes with a checksum. Messages can be longer than 21 characters when the vehicle is not moving.

The physical implementation of J1708 uses the same hardware as the RS-485 standard, but the transmitting part of the transceiver is connected as an open drain connection.
This enables several devices on the same bus and prioritizing like CAN, see Figure 2.9.

Figure 2.9: J1708 node on bus.
2.2 Measurement

The wheel loader is a heavy machine with a lot of inertia and most of the analog signals are measured on slow processes. Raising the boom from ground level to upper endpoint takes 5.4s and a whole lift cycle takes 10.0s [5]. This can be taken to account when filtering a signal. Regarding Nyquist sampling rate theorem, the sampling frequency has to be twice as high as the bandwidth of a bandwidth limited signal. Since the interesting frequency spectrum is lower than the sampling frequency, the sampling frequency can set the upper bandwidth limit for the hardware filters. It can then be digitally filtered to accommodate to the individual process that the sensor is monitoring.

2.2.1 Analog-to-Digital-Converter

An Analog to Digital Converter (ADC) converts continuous analog signals to a discrete digital representation. This means that an analog signal loses information as it is converted, because it cannot be sampled infinity fast and it does not have infinity many steps. However, this is a necessary step to be able to perform digital calculations with respect to the signal data.

Figure 2.10 shows how an analog sinusoidal signal is sampled and represented in digital form. In this case it is done in even intervals and the values on the samples are discrete integers varying from 0 to 8.

![Discrete digital representation of a analog signal.](image)

2.2.2 Digital

A digital signal is either high or low (one or zero). In an ideal case for the wheel loader it would mean that 24V is high and 0V (ground) is low. However, all the electrical devices on the wheel loader are specified to operate on a supply voltage down to 9V. This means
that a 9V digital signals should also be regarded as high with some hysteresis. That is why 8V and higher is regarded as high and 6V and lower is regarded as low, see Appendix A.

2.3 Control

The controlling device has to have outputs so it can affect a process. This sets requirements on the electronics to each output so it can handle the load of its actuator. The output channel should also handle faults that can occur on the wiring without damaging the electronics.

If, for example the output is going to control a solenoid, it sets requirements on the electronics that it can deliver enough current and voltage to open the solenoid. However it has to have protection so it handles a short circuit, ESD discharge or other scenarios that can damage the electronics. It should also be able to detect faults on its wiring and actuator.

In the case of the wheel loader, actuators can be controlled in two different ways. One way is to fake inputs to the ECU and let the ECU control the actuator. Another is to drive the actuator directly. The two different strategies can be useful in different scenarios. Driving the actuator directly may be more suitable in an control loop to avoid unwanted filtering of the signal. Faking an analog voltage to the ECU may be more suitable for remote control applications, to get the same filtering on the signal as you get when driving in the cabin.

2.3.1 Microcontroller

A microcontroller (MCU) is a small computer with integrated memory and peripherals on the same chip. It has non-volatile memory where it can store programs and parameters that will not be erased when the unit is turned off, and it has a RAM memory which it uses for temporary storage during program execution. Common peripherals in a microcontroller are hardware timers and serial communication.

This small computer is the center of a system. It takes in data from its peripherals, computes data according to the programs instructions and performs tasks to monitor and control the environment.

Hardware timers

Hardware timers enable control and monitoring of tasks with high precision. They can either contribute to an internal event in the MCU or interact with the environment through its in- and outputs, see pin\textsubscript{in} and pin\textsubscript{out} in Figure 2.11. Timers count at a given clockrate (clk\textsubscript{in}) that can be prescaled. The clock source can either be the main clock, external crystal or external event. The timer will keep counting at a given rate
independent of what tasks the CPU is preforming.

The control block controls the counter through the three signals Count, Direction and Clear. The value of the counter is stored in the Counter Reg and compared with the TOP Reg, Compare Reg and 'zero' for every cycle. If the comparators get a match they will send out signals to the Control block and Wave gen. The settings in the Control Reg determine how the Wave gen should react to the TOP and compare signal and generate an output accordingly, see “Hardware timers as PWM output”.

When the Edge detect block detects a change on the signal coming from pin\textsubscript{in} it can send a write signal to the Capture Reg and the value of the Counter Reg will be stored in Capture Reg, see “Hardware timers as event capture”.

![Diagram of a hardware timer](image)

**Figure 2.11: Overview of a hardware timer.**

### Hardware timers as PWM output

By setting a counting rate and top value, the timer will wrap around after a defined time. By also setting a compare value and some conditions for the wave generator, a PWM signal can be generated. Figure 2.12 shows a timer that sets the output when it wrap
around and clears the output when the compare value is equal to the timer value. By setting a counting rate and top value the frequency of the PWM signal is defined and changing the compare value changes the duty cycle. The PWM signal will be generated without disturbing the CPU which can perform other tasks meanwhile.

![Diagram](image)

**Figure 2.12: Hardware timer as PWM output.**

**Hardware timers as event capture**

External events can be registered by a MCU in different ways. One is to let the MCU poll a pin and check if the pins state has changed. This uses a lot of the MCUs resources and the resolution on when the event arrived is limited to how often the pin is polled. To get higher resolution, more of the MCUs resources have to be spent on polling the pin.

Another way is to connect the event to a pin that can invoke an interrupt. The interrupt will make the MCU stop executing its current function and jump to the interrupts handler. The time of the arriving event can be registered and the MCU can jump back to the code it was executing before the interrupt arrived. If the frequency of the incoming event is high, the overhead created as the MCU jumps back and forth to the interrupt handler will consume the MCUs resources. The MCUs resource usage is dependent on the frequency of the incoming event.

There is a more effective way to capture incoming events. It is to use a hardware timer to capture external events. Hardware timers can do it with high timing precision and low CPU usage. Setting a timer to count at a defined rate and letting the hardware timer save the timer value when an event arrives and then report to the CPU. Thus can the CPU process the event when there is no other prioritized tasks, and know when it arrived by reading the register where it stored the time for the incoming event.
2.3.2 SPI

Serial Peripheral Interface is used for communications between digital devices in the same system. It is a clocked bus which uses four wires to communicate. One master and several slave devices can be connected to the same bus. There are two different ways to connect slaves to the master. One is independent slave SPI configuration as seen in Figure 2.13a. And the other is Daisy chain SPI configuration as seen in Figure 2.13b.

![Figure 2.13: SPI configurations.](image)

The communication is initiated when the chip select (CS) goes low. After that the master sends one bit on the MOSI pin for every clock (CLK) cycle and the slave answers at the same time on its MISO pin from the previous command it was given. If an 8 bit-command is sent to the slave, the master has to send 8 more bits so the slave can answer to the sent command.

Figure 2.14 shows how the master initiates the communication and sends the command ‘14’ to the slave, and the slave answers from the previously sent command with the value ‘67’.

2.3.3 DAC

To convert a Digital value to an analog voltage, a Digital to Analog Converter is used. It represents a digital value as a discrete analog voltage. This makes it possible to recreate signals previously sampled by a ADC. But as Figure 2.15 shows, the signal is not identical to the one sampled in Figure 2.10.

The analog output can be used to fake input signals to the ECU. However the analog signal has to be buffered so it can deliver enough current to handle the pull up and pull down resistors in the ECU. It can be done through an operational amplifier that is coupled as a voltage follower.
2.3. Control

2.3.4 Power electronics

To control the solenoids on the wheel loader four different techniques was evaluated. As it turned out, only two could handle the specification in appendix A. Concept 3 and 4 had enough fault detection and could handle short circuits to ground, however concept 4 had too many components and was too expensive. Therefore concept 3 was chosen for both PWM out and Solenoid out.

The transistors for the power electronics should control loads that have an internal resistance of around 20Ω. The load is the coil in the solenoids that controls the hydraulic valves. Inductive loads such as a coil needs a freewheel diode $D_f$ that bypasses the current as the transistor is turned off, see Figures 2.16 - 2.19. Without the diode the current that is flowing through the coil will generate a voltage that is high enough to either charge the parasitic capacitances, creating a short circuit by exceeding the breakthrough voltage of the transistor or generate a spark which can damage the electronics.

When using PWM to drive an inductive load, the transistor is often turned on while the freewheel diode is still conducting a current. If the reverse recovery time of the free wheel diode is longer than the ramp times on the transistor it will create a short circuit.

Figure 2.14: Bit timing between master and slave.

Figure 2.15: Discrete analog representation of a digital value.
just as the transistor is turned on. This will generate transients on the power lines that can radiate to other electronic circuits. To minimize the short circuit time the reverse recovery time on the free wheel diode should be kept to a minimum. For normal PN-junction diode it takes some time before the charges in the junctions is dissipated and the diode is turned off [11]. However, Schottky diodes does not have to deplete any charge for it to turn off. This gives Schottky diodes shorter reverse recovery time than normal PN-junction diodes. That is why Schottky diodes are used in PWM applications.

**Concept 1**

Figure 2.16 shows a concept that uses a P-channel MOSFET to control the Load, where one end of the load is connected to the transistor and the other to ground.

P-channel MOSFETs are less effective than N-channel MOSFETs because the nature of physics that make them conduct. Electrons in the substrate moves easier than 'holes', thus giving P-channels a higher resistance [12].

This concept uses few components but it is ineffective, has no protection against a short circuit in the outgoing wires and no current measurement.

![Figure 2.16: Concept 1 PWM out schematic.](image)

**Concept 2**

Figure 2.17 shows a concept that connects one end of the load to +24V and the other end to a N-channel MOSFET. To draw current through the load, the transistor is turned on and sinks it to ground.

This concept is cheap, effective and uses few components but it has no protection if the wires are short circuited and it has no current measurement.

**Concept 3**

Figure 2.18 shows a concept that uses a smart high side switch that has internal protection against short circuit and high temperatures. It also measures the current that is flowing
2.3. Control

Figure 2.17: Concept 2 PWM out schematic.

through the transistor and can detect if the circuit is open.
This smart high side switch is connected to one end of the load and the other end of
the load is connected to ground.
This concept uses few components, measures the current and has protection against a
short circuit on the transistor side, but is has no protection if the outgoing ground wire
is short circuited to +24V.

Figure 2.18: Concept 3 PWM out schematic.

Concept 4

Figure 2.19 shows a concept that uses a smart high side switch that has internal protection
against short circuit and high temperatures. It also measures the current that is flowing
through the transistor and can detect if the circuit is open.
This smart high side switch is connected to one end of the load and the other to an
N-channel MOSFET that has a shut resistor $R_s$. The current flowing through the shunt
resistor is continuously measured and if it exceeds a threshold level it will shut off the
lower N-channel transistor.
This concept has short circuit protection on all outgoing wires and measures the current
but it is expensive and uses many components.
The third concept that was shown in Figure 2.18 was used in the final design, see
Result. It meets the requirements of the specification and uses less components than concept four (Figure 2.19).
2.4 Safety and Regulations

Since the unit is only a prototype it does not need to comprehend all the demands in the "ISO 26262 Achieving Functional Safety in the Automotive Industry". But some sort of security is needed to not endanger people or other property.

2.4.1 Emergency shutdown

If the EBU is going to take over the movement of the wheel loader, there has to be some sort of fail-safe so it can be stopped if something goes wrong. The EBU has to be able to shutdown remotely and from on board the wheel loader. Both the remote and on board shutdown switches can be coupled in series so if any of them opens their circuit, it will cut the power to the EBU.

2.4.2 Watchdog

One way to monitor that the MCU is not in any undefined state is to have the operating system control an external pin that pokes an external watchdog. The watchdogs job is to reset the MCU if the system crashes.

If the watchdog is windowed (WWDT), it means that the MCU cannot poke the watchdog to often or to seldom as Figure 2.20 shows. That will be regarded as faulty behavior and the watchdog will reset the system by pulling the reset pin on the MCU.

![Figure 2.20: How a windowed watchdog operates.](image-url)
2.4.3 EMI

Electromagnetic Interference, it is when unwanted signals/transients radiate to other circuitry. This can cause problems and even destroy other circuitry, especially in a vehicle where several different systems are connected to each other and exposed to a harsh environment. That’s why there are several different Electromagnetic Compatibility (EMC) standards that defines how much interference each system is allowed to radiate, and how immune the system should be for incoming interference [13].

All digital circuits are composed of several transistors, often CMOS transistors. When these transistors changes state, like when a gate changes output from low to high, there will be some short circuit current when both the upper and lower transistor is on. Another problem is the gate capacitance in the transistors, it has to be dissipated and this will consume a current when the transistor change state. Hence, switching a transistor will generate a current spike that will lower the voltage over the circuit just when the switching takes place [11].

When a digital circuit is clocked, saying that it will change state continually with even intervals. It will generate current spikes on its power lines with even intervals. Each spike can be approximated as a square wave impulse. Since a square wave can be described with the sum of infinity many sinusoidal harmonics, the circuit will radiate infinity many sinusoidal harmonics on the power lines.

\[
x_{\text{square}}(t) = \frac{4}{\pi} \sum_{k=1}^{\infty} \frac{\sin(2\pi(2k-1)\omega t)}{(2k-1)}
\]

Figure 2.21 shows how the current spikes on the power lines can be reduced. The decoupling capacitor \( C_d \) is physically placed close to the power pins on the MCU giving it low resistance and inductance. This will keep the voltage level steady as the CMOS circuitry draws current in even intervals shown as \( i_3 \). To minimize the RF radiation from the spikey current loops, the loop area should be as small as possible.

The capacitor \( C_e \) is further away from the MCU so the power lines are longer, this will give stray resistance \( R_s \) and inductance \( L_s \). \( R_s \), \( L_s \) and \( C_e \) can be seen as a low-pass filter and smoothes out the spikes in the current loop \( i_2 \). This current loop area should also be kept to a minimum to minimize the RF radiation.

The EMI filter in this case is shown by \( L_{\text{emi}} \) and \( C_{\text{emi}} \). They are designed to attenuate the high frequency harmonics that comes from switching devices so they will not spread to other circuitry. The area of \( i_1 \) is dependent on the distance between the power source and the device, in the case of a vehicle it is the length of the wires between the battery and device.
Figure 2.21: How decoupling and EMI filters attenuate current spikes on power lines.
The result of this thesis is an Electronic Breakout Unit that can be connected directly onto the original wiring on the wheel loader. The system monitor and control all signals that are going through the wires. Communication with the outside world, i.e. a PC, is done through Ethernet. As seen in Figure 3.1, the system consist of two separate Printed Circuit Boards (PCB) that are stacked upon each other.

The topmost card is the Relay Card. All the original wiring is connected directly to this card. This gives the EBU access to all the sensors and actuator signals on the wheel loader. To provide a good interface to the original wiring it uses the same connectors as the original ECUs. It also has the capability to disconnect itself from the wires to ensure that it will not interfere with unwanted signals. The functionality of the Relay Card is further explained in Section 3.1.

The card at the bottom in Figure 3.1 is the Control Card of the EBU. Its purpose is to monitor and control the signals that are connected to the Relay Card, and communicate that information to the outside world through Ethernet. How the monitoring and control of the signals are dealt with is further explained in Section 3.3.
3.1 Relay Card schematic

The Relay Card is connected in between the wheel loaders wiring and the ECU. This makes it possible to monitor and control signals in both directions. To do so the incoming and outgoing wire through the EBU has to be disconnected from each other. Otherwise two control sources will be connected on to the same wire and they will short circuit each other.

To disconnect the incoming and outgoing wire, and at the same time connect the wire to the Control Card, a relay used. This enables for example monitoring of a sensor while sending an emulated sensor signal to the ECU. It also ensures that the EBU can not interfere with signals it’s not supposed to control and that the whole EBU can be disconnected from the wiring by cutting the power to the relays. When the power to the relays are cut they return to their idle state, this disables the EBU to control the wheel loader and is used as a safety precaution. If a malfunction in the system takes place and the wheel loader has to be stopped the power to the relays can be cut and the whole EBU will be just like a straight through cable, connecting the wheel loaders wiring directly to the ECU.

The Relay Card is stacked upon the Control Card as seen in Figure 3.1. If a signal is to be controlled, the Relay Card switches the relays so the Control Card is connected to the wire. Then the Control Card can send and receive information to both the wheel loader and to the original ECU. This setup does allow the EBU to both listen, as well as take full control of all the different signals on the wheel loader. One example is for instance the tilt of the bucket. Normally the tilt is controlled by an electrical lever in the cabin. Using the EBU, the signal from this lever could be emulated and in turns, the tilt of the bucket may be controlled without touching the lever.

![Figure 3.1: The Electronic Breakout Unit is divided into two printed circuit boards, a Relay Card, and a Control Card.](image-url)
3.1. Relay Card schematic

3.1.1 Digital in and Digital out

Digital signals are widely used on the wheel loader. Such signals can come from interface buttons, digital sensors or other digital electronics.

As seen in Figure 3.2 the original wiring is connected to the EBU, and the EBU is connected to the ECU. The Relay Card connects the signal to the ‘Digital in’ port on the Control Card, so the Control Card can always listen to the signal. To be able to tamper with the signal that is going to the ECU a relay has to be switched, connecting the ‘Digital out’ port on the Control Card to the wire that is going to the ECU.

Some of the digital signals require a pull up or down resistor. Therefore, there are empty soldering pads where pull up and pull down resistors can be mounted, shown as gray in Figure 3.2. These are meant to customize each input on the Relay card so they match the ECU its monitoring. The resistor is then connected to the wire as the relay switches, and the EBU takes control of that signal.

3.1.2 Analog in and Analog out

There are several analog signals connected to the EBU. They are either generated by user interface sensors or sensors that measure some physical property of the wheel loader. All the sensors are designed to deliver an analog output between 0.5V to 4.5V.

As seen in Figure 3.3 the original wiring is connected to the EBU, and the EBU is connected to the ECU. The Relay Card connects the signal to the ‘Analog in’ port on the Control Card, so the Control Card can always listen to the signal. To be able to tamper with the signal that is going to the ECU a relay has to be switched. When switched, the ‘Analog out’ port on the Control Card is connected to the wire that is going to the ECU. This enables to send emulated input to the ECU, like tilting the bucket.

As for the Digital in and out ports there are resistor pads that allows the input to customized dependent on which signal its monitoring. The resistor (shown as gray in
Figure 3.3) are then connected to the wire as the relays switches.

![Diagram showing relay connecting wires](image)

Figure 3.3: The relay connects the pull up/down resistors to the wire at the same time the Analog out is connected to the ECU.

### 3.1.3 Solenoid out and Load Resistor

The main actuators on the wheel loader are hydraulic valves which are controlled by solenoids. As seen in Figure 3.4 the original wiring is connected to the EBU, and the EBU is connected to the ECU.

The ‘Solenoid in’ port on the Control Card is always connected to the wire so the EBU can listen what the ECU sends out. However the EBU cannot send out any signal to the original wiring unless the relay is switched. With the relay switched, the ‘Solenoid out’ port is connected to the outgoing wire and the EBU can control the solenoid. The relay also connects a load resistor to the ECU so it will not detect any faulty wiring.

![Diagram showing relay connecting load resistor](image)

Figure 3.4: The relay connects the load resistor to the ECU and bypasses the signal to the Control Card.
3.1.4 PWM out and Load Resistor

Some of the hydraulic valves on the wheel loader are of a proportional type, i.e. it is possible to proportionally control the flow of fluid through them. The solenoids in those valves are controlled by a PWM signal which both has an outgoing wire and a return wire as seen in Figure 3.5. The original wiring is connected to the EBU, and the EBU is connected to the ECU.

The ‘PWM in’ port on the Control Card is always connected to the outgoing wire so the EBU can listen what the ECU sends out. However the EBU cannot send out any signal to the original wiring unless the relay is switched. By doing so, both the outgoing and return wire is connected to the ‘PWM out’ port and the EBU can control the solenoid. The relay also connects a load resistor to the ECU so it will not detect any faulty wiring.

![Figure 3.5: The relays connects the load resistor to the ECU and bypasses the signal to the Control Card.](image)

3.1.5 CAN and J1708

For every CAN and J1708 bus on the ECU, the EBU has two transceivers. One that is always connected to the original wiring and one that can be connected to the ECU. This enables filtering of messages and control of other peripheral equipment.

The transceiver that is connected to the ECU always has a terminating resistor connected between the two wires. The transceiver that is connected to the outgoing wires has a terminating resistor that can be connected as the relay is switched as Figure 3.6 shows.

3.1.6 Relay drivers

All the relays on the Relay Card are controlled by an I/O-extension through a SPI bus, which is explained further in Section 3.3.4 “Internal buses”. Figure 3.7 shows how the output from the shift register IC1 is connected to the relay driver IC4 ULN2803. The
Figure 3.6: The relay connects the terminating resistor to the original wiring and connects the ECU to the Control Card at the same time.

relay driver ULN2803 has internal freewheel diodes which can drain 500mA [14], therefore external freewheeling diodes are unnecessary.

Figure 3.7: Relay driver schematic.
3.2 Relay Card layout

The connectors in the upper part of Figure 3.8 connects the EBU to the wiring on the wheel loader. The connectors on the bottom connect the EBU to the original ECU. The main relay can cut the power to the power electronics and relays.

All analog signals is kept as far as possible from the switching power signals to minimize interference. The pull up/down and load resistors are all placed on the bottom of the card. This makes it easy to distinguish the customizable resistors from the permanent static resistors.

The PCB card has 6 layers of copper which connects the pads on the components. The routing of each layer can be seen in Appendix C.

Figure 3.8: Layout of the Relay Card and its internal blocks.
3.3 Control Card schematic

The Control Card is stacked upon the Relay Card as Figure 3.1 shows. One task for the Control Card is to monitor electrical signals and transmit data over Ethernet. It can also control some of the signals that are going to the wheel loader and to the ECU.

The tasks of the Control Card is divided over three Microcontrollers (MCU). The main reason why three MCUs had to be used is the number of CAN buses to be monitored, and the numbers of hardware input captures.

As Figure 3.9 shows, there is one master and two slave MCUs. The one in the middle is the master MCU, it has one SPI bus that is connected to the lower speed peripherals e.g. ADC, DAC, 'Digital in/out’, ‘Solenoid out’ and the relays. The master handles the Ethernet communication and streams the data to and from the two slaves through dedicated SPI buses and transmit them over Ethernet.

The slave MCUs are connected to the master through SPI buses. The slaves share the high speed peripherals e.g. CAN communication, Frequency in and PWM out and transmits there data to the master on the masters request.

![Diagram of Control Card schematic](image)

Figure 3.9: System overview of the Control Card.

3.3.1 Power supply

The in-coming power first goes through a protection circuit as Figure 3.10 shows. It protects the EBU from incoming transients and load dumps (Appendix A). The input power is then divided into '24V power', '24V regulated’ and power to the digital circuitry.

The '24V power' is the supply that drives the hydraulic valves. The switching frequency of the power electronics is 200Hz and it is switched softly. Softly implies that the rise and fall times on the transistor that is controlling the signal is limited. This lowers the radiated harmonics so no EMI filter should be necessary. The '24V power' supply can
be turned on and off through a N-channel MOSFET.

The ’24V regulated’ is used to supply the Digital out ports. The Digital out ports does not change its state more often than the sampling rate, which is 50Hz. Hence, no EMI filter should be needed for this signal. The allowed current limit is below 1A so a linear regulator LM317HV was chosen.

The internal digital components demands two different voltage supplies, one 3.3V and one 5V. The specification in Appendix A states that the EBU should be able to operate at a battery voltage between 9 – 60V. To comprehend with such a large voltage span and still keep the energy losses to a minimum, a switched regulator had to be used. The switched voltage regulator is behind an EMI filter and it regulates the voltage down to 8V and sends it to two linear regulators. One that regulates the voltage to 3.3V to supply the MCUs with power, and another one that regulates the voltage to 5V to supply the peripherals on the board.

The analog voltage supply is taken from the analog supply output from the ECU and has the same ground reference as the analog ground on the ECU. The analog circuitry is galvanically separated from the EBU. This setup should decrease the interference and potential grounding loops. All communication to the analog circuitry is done through galvanically separated transceivers. However, if the analog circuits draw to much current from the ECU, the circuit board is prepared for adding a filtered 5V analog voltage supply that can be generated through the 5V supply as Figure 3.10 shows.

![Figure 3.10: Overview of the power supply.](image)

**Emergency shutdown**

If the EBU is going to take over the movement of the wheel loader there has to be some sort of fail-safe so it can be stopped if something goes wrong. That is why an external emergency switch will be mounted on the wheel loader. The emergency switch can be
controlled from inside the cabin and remotely through wireless communication. By using this emergency switch to cut the power to units that control the wheel loader will bring the wheel loader to a halt.

The wheel loader can be shut down in two ways when it’s controlled remotely. One way is to cut the power to the whole wheel loader, this will shutdown all electronic equipment on the wheel loader and it will eventually come to an abrupt halt. Another way is to just cut the power to the relays in the EBU as Figure 3.11 shows. If only the power to the relays is cut off, the unit will not be able to control any signals but it will still be possible to monitor and log data.

Figure 3.11: Overview over the built in safety features. The emergency switch is external equipment and not included in this thesis.
3.3. **Control Card schematic**

**Power in**

The main battery is connected to 'BATTF' in figure 3.12 through a main relay. 'BATT ON' is the net that supplies the power transistors and can be turned off and on by the MOSFET Q1. The MOSFET Q1 is controlled by the signal 'ON' from the master MCU.

The D5 diode is a reverse protection diode that will blow the fuse to the EBU if the battery poles are switched. The diodes D3 and D4 supplies the voltage regulators for the digital circuits.

![Figure 3.12: Power in schematic.](image)

**Switched regulator 8V and 32V**

A switched regulator was chosen to be able to deliver enough current to all the digital circuits and keeping the energy losses to a minimum as the voltage is lowered. The switched regulator 'LM5575MH' has an internal P-channel MOSFET that can either turn on or off the current flowing from pin3 to pin14, see Figure 3.13. This MOSFET is controlled by the internal logical circuits inside the 'LM5575MH' chip. The frequency of how fast the regulator should switch this MOSFET is determined by the resistor R16 on pin7. A value of 21kΩ on R16 should give a frequency of 300kHz [15]. How long time the MOSFET should be on during each cycle is determined by the voltage on pin6. The current values of the two resistors R23 = 10kΩ and R24 = 1.8kΩ should give a duty cycle that keeps a steady 8V output from the pin on inductance L2 that is connected to the '8V' net.

The 32V is needed to drive the N-channel MOSFET that delivers the power to the power electronics. It is generated through a charge pump. As pin14 switches and goes
below 8V the capacitor C68 is charged through the diode D6. When pin14 rises back up to the battery voltage, the charge in C68 is pumped to C71 through the other diode in D6. Thus giving a voltage potential that is 8V above the battery voltage. The regulator is behind an EMI filter L3 that attenuates the harmonics on the power line.

Figure 3.13: Switched regulator 8V and 32V schematic.

3.3.2 Inputs

Analog in

The 'Analog in' ports samples the analog voltage signals from the sensors on the wheel loader. If the signal is to be controlled from the EBU, a pull up/down resistor, shown in gray in Figure 3.14, is mounted on the Relay Card.

To attenuate interference a low pass filter between $R_1$ and $C_1$ is designed. This gives a cutoff frequency of:

$$f_c = \frac{1}{2\pi R_1 C_1}$$

To protect the ADC two external protection diodes is placed rail-to-rail with the signal net. The signal is then measured by the ADC and read by the master MCU through a SPI bus.
3.3. Control Card schematic

In Figure 3.14: Analog in schematic.

Digital in

The Digital in ports both listens to the digital output that the wheel loader is providing and to the solenoid outputs from the ECU. If the signal is to be controlled from the EBU, a pull up/down resistor, shown in gray in Figure 3.15, is mounted on the Relay Card. A digital 'High' should be considered as 'High' even if the battery voltage varies between 9 – 60V. That sets the condition for the voltage division between $R_1$ and $R_2$:

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2}$$

To reduce influence of button bounce and other interference a low pass filter between $R_1$, $R_2$ and $C_1$ is designed. The cutoff frequency of the filter is calculated as:

$$f_c = \frac{1}{2\pi (R_1 || R_2) C_1}$$

To protect the logical circuit two external protection diodes is placed rail-to-rail with the signal net. The signal is then sent to a shift register that is controlled by the master MCU, this is further explained in Section 3.3.4 “Internal Buses“ on page 43.

In Figure 3.15: Digital in schematic.
Frequency in

The velocity sensors on the wheel loader are all of the inductive type described in Chapter 2. These sensors induce a sinusoidal voltage signal of which the frequency is directly proportional to the measured velocity. However, the amplitude of the signal does also vary with the velocity hence a special designed circuit, the LM1815, is used to amplify and detect the signal. The LM1815 uses an adaptive hysteresis to reduces the errors if the signal is interfered and adapts the hysteresis to the amplitude of the sinusoidal signal.

If $C_1 >> C_2$ then the circuit in Figure 3.16 can be considered a band-pass filter. This filters is designed to let through the wanted mid frequency spectrum and attenuate the unwanted low and high frequencies. Unwanted frequencies in this case can be DC offset and high frequencies from switching electronics.

The bandpass filter has a lower cutoff frequency of:

$$f_L = \frac{1}{2\pi R_2 C_1}$$

And an upper cutoff frequency of:

$$f_H = \frac{1}{2\pi R_1 C_2}$$

The LM1815 chip measures the zero crossing of the sinusoidal signal and represents it as a digital signal. The digital signal is then sent to a pin on the MCU that can use hardware timers to measure the frequency of the signal, see "Hardware timers as event capture".

3.3.3 Outputs

Analog out

The 'Analog out' ports sends analog signals to the wheel loader’s ECU emulating sensors or driver input. It is done through a DAC that is controlled by the master MCU. The maximum output current from the DAC is highly limited so an operational amplifier (op amp) is connected as a buffer on the signal. The resistance $R1$ connected in series with
the output of the op amp is there to protect the op amp from high currents that might occur if the output for some reason is short circuited. \( R_1 \) and \( C_1 \) creates a low pass filter that limits the high frequency output.

\[ \begin{align*}
\text{From DAC} & \quad R_1 & \quad \text{Out} \\
\text{\quad} & \quad - & \quad \text{\quad} \\
\text{\quad} & \quad + & \quad \text{\quad} \\
\end{align*} \]

Figure 3.17: Analog out schematic.

**Digital out**

The 'Digital out' port is used to send digital signals to the wheel loader ECU to be able to emulate driver and sensor input. It is controlled by the master MCU through a shift register, this setup is further explained in Section 3.3.4 "Internal Buses" on page 43.

The digital signal from the shift register is represented as \( 0V \) or \( 5V \), it has to be amplified so it can go from \( 0V \) to \( 24V \). It is done through a buffer. The series resistance \( R_1 \) is there to protect the buffer from breaking by drawing too much current if the outgoing wire is shorted, see Figure 3.18. The resistor \( R_1 \) and the capacitor \( C_1 \) also constructs a low pass filter that limits the outgoing frequency output from the port. This is done for lowering the amount of interference that the EBU is radiating.

\[ \begin{align*}
\text{From shift reg} & \quad +24V & \quad R_1 & \quad \text{Out} \\
\text{\quad} & \quad - & \quad \text{\quad} & \quad \text{\quad} \\
\text{\quad} & \quad \text{\quad} & \quad \text{\quad} & \quad \text{\quad} \\
\end{align*} \]

Figure 3.18: Digital out schematic.
**PWM out**

The 'PWM out' ports are controlled by output pins on the MCU. These pins generate a PWM signal by using a hardware timer which is further explained in Section 2.3.1 “Hardware timers as PWM output”.

Figure 3.19 shows the design of the 'PWM out' port, it uses a smart high side switch that has internal protection against short circuit and high temperatures. Besides that, it measures the current that is flowing through the transistor and it can detect if the circuit is open.

This smart high side switch is then connected to one end of the load and the other end of the load is connected to ground.

![PWM out schematic](image)

Figure 3.19: Concept 3 PWM out schematic.

**Solenoid out**

'Solenoid out' uses the same power electronics as 'PWM out' but the controlling signal comes from a shift register instead of a pin from the MCU, see Figure 3.19. It also measures the current that is flowing through the transistor and can detect if the circuit is open.

3.3.4 Microcontroller and peripherals

The microcontroller (MCU) LPC1768 from NXP semiconductors is used to control the EBU. It has CAN, Ethernet, PWM output, SPI and many more peripherals and can execute instructions at 100 MHz [16]. Since it only has two CAN modules and six PWM out, several MCUs has to be used to be able to control and monitor all signals that is connected to the EBU.
3.3. Control Card schematic

Watchdog

The external watchdog MAX6753 is used to reset the MCUs if they come in some undefined state. It also resets the relays so that they are switched to their idle state. This disconnects the Control Card from the original wiring, thus ensuring that the EBU will not come in some undefined state and controlling the wheel loader.

The MAX6753 chip has a windowed watchdog which needs to be reseted with even intervals. If the watchdog is reseted to fast or slow it will reset the MCUs [17]. The interval that the watchdog has to be reseted is set to 100ms by the capacitor C79 as seen in Figure 3.20. The window for a successful reset is set by the pull up/down resistors on pin 1 and 5.

![Watchdog schematic](image)

Figure 3.20: Watchdog schematic.

Internal buses

The internal and external digital in and out ports on the EBU far exceeds the input and output pins on the MCUs, hence an I/O-extension is needed. This is done by using shift registers, where the output to the shift registers is shifted out from a SPI bus on the MCU. As the MCU shifts out the output it also reads the values that is shifted to it from the input shift registers. To connect this I/O-extension to a SPI bus where several other devices can be connected, a tri-state gate has to be placed on the MISO pin as Figure 3.21 shows. The MISO pin from the I/O-extension should be at high impedance state when the I/O-extension is inactive (Chip Select, CS high).

The shift registers are coupled in series, and as CS is enabled the input shift registers stores the input. As the MCU starts the clock pulses on SCK and writes on MOSI to the output shift register, the input register starts to shift out their input to the MCU. At the same time as the new output is written to the output shift register, the input registers
answers with their input. When the CS is disabled the output registers changes state to what is written in their internal registers.

Figure 3.21: Tri-state gates and shift registers expand the digital I/O.

Figure 3.22: SPI I/O Extension schematic.

To measure the analog signals with the same reference as the original ECU, the analog devices in the EBU must be on the same ground as the analog ground on the ECU. To
ensure that no ground loops are created which can pick up interface, the communication between the analog devices and the rest of the EBU had to be isolated. The ADUM7441 uses internal transformers to isolate the communication and can handle speeds up to 25Mbit [18]. As seen in Figure 3.23 the ADUM7441 isolates the communication between the MCU and analog devices.

The ADCs cannot be connected in daisy chain so each of the devices has to have one separate CS net. But the DACs can be connected in daisy chain, so it reduces the number of nets that has to be isolated.

Figure 3.23: SPI Isolated schematic.
3.4 Control Card layout

Figure 3.24 show how the input and output circuits are placed on the board. The analog side to the left is galvanically separated from the rest of the board and is placed as far as possible from the high current switching electronics.

The blocks that handle high frequency signals are placed closer to the MCU. This is to keep the path between the devices as short as possible to minimize the current loop which lowers the intensity on the radiated frequencies.

Figure 3.24: Layout of the Control Card and its internal blocks.
Chapter 4

Conclusions

The EBU system presented in this thesis allows signals on the wheel loader to be controlled over Ethernet. It makes it possible to send driver-input remotely and control actuators directly. This makes it easy to test and develop new functionality and driver support systems on the wheel loader. It allows new ideas and concepts to be tested without having to make any changes on the wheel loader except from connecting the EBU. All software on the ECUs can be untouched and the add-on system can be installed in a short time and it is easy to remove. With the EBU removed the wheel loader is back to its original state without any damages on its original systems.

I hope that my work will improve the testing and developing phase at Volvo Construction Equipment, and come in good use to them.

4.1 Future work

Hardware

There are still things that has to be done until the EBU can be mounted and used in the wheel loader.

- Stress test, inputs, outputs, power supply and the safety features so they can handle the specifications in Appendix A.

- The PCB cards are designed to fit in a aluminum casing which protects the electronics, and dissipates heat from the transistors. However, the casing has to be machined to fit the connectors and mounting brackets.

- The system has to be mounted and tested in the wheel loader.
Software

- Software has to be developed for the individual MCUs. The two slave MCUs should have the same software and shouldn’t be too complex to write. However, the master MCU probably needs to use its DMA to be able to stream everything over Ethernet.
- Develop an protocol to transmit/receive data to/from the on-board PC.
- Software testing and debugging.

Interface

- Develop an interface to Matlab and Simulink so VCE and LTU can use it to easily develop and test functions and control algorithms on the wheel loader.

4.2 Fields of application

The main use for the EBU is to monitor and control the wheel loader. It allows testing of new prototypes and functions on the wheel loader and has the capability to stream large amounts of data to an on-board PC. When testing and developing new ideas and concepts on the wheel loader, the original electronics be untouched and just let the EBU control the new function. Since the EBU monitors all the sensors on the wheel loader the original sensor data can be used to control the new function.

LTU is going to use the EBU to develop and test new techniques to lower the fuel consumption on a four wheel drive vehicle with articulated angle, like the wheel loader. It is also going to be used to develop advanced remote control and driver assistance systems.

Several student projects are going to use it to gather data from the wheel loader. The projects are going to focus on building new sensors and features for the wheel loader, to increase the knowledge of the surrounding environment.

The Electronic Breakout unit is a general purpose device that can be used for other Volvo vehicles as well. However, the pinout of the connectors are matched to the L110G wheel loader. The EBU can be used to control and log other systems over Ethernet that is within the specifications in Appendix A.
REFERENCES


APPENDIX A

Specification
The unit shall monitor and take over selected channels to and from the ECU without disturbing the original electronics and damaging the original wiring.

<table>
<thead>
<tr>
<th>Type</th>
<th>EBU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog IN</td>
<td>20</td>
</tr>
<tr>
<td>Digital IN</td>
<td>38 + 22</td>
</tr>
<tr>
<td>Frequency IN</td>
<td>6 + 16</td>
</tr>
<tr>
<td>Analog OUT</td>
<td>20</td>
</tr>
<tr>
<td>Digital OUT</td>
<td>38</td>
</tr>
<tr>
<td>Frequency OUT</td>
<td>6</td>
</tr>
<tr>
<td>Solenoid OUT</td>
<td>22</td>
</tr>
<tr>
<td>PWM OUT</td>
<td>16</td>
</tr>
<tr>
<td>Load resistor</td>
<td>22 + 16</td>
</tr>
<tr>
<td>J1708</td>
<td>2 x 1</td>
</tr>
<tr>
<td>CAN</td>
<td>2 x 2</td>
</tr>
<tr>
<td>Ethernet</td>
<td>1</td>
</tr>
<tr>
<td>KEY</td>
<td>1</td>
</tr>
<tr>
<td>BATT</td>
<td>2</td>
</tr>
<tr>
<td>24V</td>
<td>2</td>
</tr>
<tr>
<td>5V</td>
<td>3</td>
</tr>
<tr>
<td>PWM Ret</td>
<td>16</td>
</tr>
<tr>
<td>misc.</td>
<td>7</td>
</tr>
<tr>
<td>FGND</td>
<td>1</td>
</tr>
<tr>
<td>AGND</td>
<td>2</td>
</tr>
<tr>
<td>GND</td>
<td>2</td>
</tr>
<tr>
<td>NC</td>
<td>3</td>
</tr>
</tbody>
</table>

**Power Supply**

- Operating range: 9 - 60 V

**Security**

- Manual emergency shutdown
- Remote emergency shutdown
- Windowed Watchdog

**Analog IN**

- Measure range: 0 - 5 V
- Max range: -100 - 100 V
- Resolution: Min 12 bit
- Bandwidth: 0 - 1k Hz
<table>
<thead>
<tr>
<th><strong>Digital IN</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>High</strong></td>
<td>8 – 100 V</td>
</tr>
<tr>
<td><strong>Low</strong></td>
<td>-100 - 6 V</td>
</tr>
<tr>
<td><strong>Max range</strong></td>
<td>-100 - 100 V</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>Min 50 Hz</td>
</tr>
<tr>
<td><strong>Interrupts</strong></td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Frequency IN</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bandwidth</strong></td>
<td>1 – 10k Hz</td>
</tr>
<tr>
<td><strong>Max range</strong></td>
<td>-100 - 100 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Analog OUT</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Update freq.</strong></td>
<td>Min 50 Hz</td>
</tr>
<tr>
<td><strong>Output range</strong></td>
<td>0 – 5 V</td>
</tr>
<tr>
<td><strong>Short circuit prot.</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Output current</strong></td>
<td>Max 80 mA</td>
</tr>
<tr>
<td><strong>Impedance</strong></td>
<td>47 ohm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Digital OUT</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>Update freq.</strong></td>
<td>Min 50 Hz</td>
</tr>
<tr>
<td><strong>Output range</strong></td>
<td>0 – 24 V</td>
</tr>
<tr>
<td><strong>Short circuit prot.</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Output current</strong></td>
<td>Max 0.6 A</td>
</tr>
<tr>
<td><strong>Impedance</strong></td>
<td>150 ohm</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Solenoid OUT</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Update freq.</strong></td>
<td>Min 50 Hz</td>
</tr>
<tr>
<td><strong>Output range</strong></td>
<td>0 – 24 V</td>
</tr>
<tr>
<td><strong>Short circuit prot.</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Output current</strong></td>
<td>5 A</td>
</tr>
<tr>
<td><strong>Impedance</strong></td>
<td>Max 0.5 ohm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>PWM OUT</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Switching freq.</strong></td>
<td>10 – 1k Hz</td>
</tr>
<tr>
<td><strong>Update freq.</strong></td>
<td>Min 50 Hz</td>
</tr>
<tr>
<td><strong>Output range</strong></td>
<td>0 – 24 V</td>
</tr>
<tr>
<td><strong>Short circuit prot.</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Output current</strong></td>
<td>5 A</td>
</tr>
<tr>
<td><strong>Impedance</strong></td>
<td>Max 0.5 ohm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>CAN</strong></th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Baudrate</strong></td>
<td>250k bit/s</td>
</tr>
<tr>
<td></td>
<td>Baudrate</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>J1708</strong></td>
<td>9600 bit/s</td>
</tr>
<tr>
<td><strong>Ethernet</strong></td>
<td>10 – 100M bit/s</td>
</tr>
</tbody>
</table>
Relay Card Schematic
Power and Ground

The names on pins and nets have been erased on request from the customer.

VARISTORCN0603 1n/100V

VARISTORCN0603 1n/100V

VARISTORCN0603 1n/100V

VARISTORCN0603 1n/100V

VARISTORCN0603 1n/100V

VARISTORCN0603 1n/100V
The names on pins and nets have been erased on request from the customer.
The names on pins and nets have been erased on request from the customer.
Solenoid

The names on pins and nets have been erased on request from the customer.
The names on pins and nets have been erased on request from the customer.
Communication

The names on pins and nets have been erased on request from the customer.
I/O ports
Relay drivers
APPENDIX C

Relay Card Layout
Top components
Bottom components
Layer 1 (Top)
Layer 2
Layer 3
Layer 14
Layer 15
Layer 16 (Bottom)
APPENDIX D

Control Card Schematic
I/O ports
Slave MCU 1
# Power supply

Battery to 24V

BATT to 32V and 8V

8V to 3.3V

8V to 5V and 5V analog

BATT to 32V and 8V
Solenoid out
PWM out
Digital out

Place caps close to port

74HC595D

L293DD

+24V

+5V

VSS

VSS

VSS

VSS

VSS

VSS

VSS

+5V

100n

100n

150

150

150

150

150

150

150

150

150

150

150

150

150

C104

C105

C106

C107

C108

C283

C284

C285

C286

C287

C288

C289

C290

D_CLK

D_CS

DO1_HA9

DO2_EA14

DO3_EA13

DO4_EA12

DO5_EA11

DO6_EA10

DO7_EA9

DO8_EA8

DO_SER1

DO_SER

D_RST

A

B

C

D

E
Place caps close to port
Place caps close to port

74HC595D... DO_SER2 D_RST

ABCDE
ABCDE
1 2 3 4 5 6

Place caps close to port
Place caps close to port

74HC595D... DO_SER2 D_RST

ABCDE
ABCDE
1 2 3 4 5 6
Place caps close to port

74HC595D

L293DD

+24V

+5V

100n/60V

VSS

VSS

VSS

+5V

VSS

150

150

150

150

150

150

150

150

1n/100V

1n/100V

1n/100V

1n/100V

VSS

VSS

VSS

VSS

VSS

VSS

1n/100V

1n/100V

1n/100V

1n/100V

VSS

VSS

VSS

VSS

VSS

VSS

C124

C125

R84

R85

R86

R87

R88

R89

R90

R91

IC34

GND

VCC

DO37_EB20

DO38_EB19

DO39_EB18

N$68

DO33_EA50

DO34_EB23

DO35_EB22

DO36_EB21

DO_SER4

DO_SER5

D_RST

ABCDE

1 2 3 4 5 6
Digital in
Analog in
Analog out
Frequency in
LM1815M
+3V3
VSS
100n
18k
+3V3
VSS
1.6M
220n
VSS
+3V3
VSS
5.6k
100n/100V
1k
47p
GND
2
VIN
3
MODE
5
PEAK_CAP
7
VCC
8
TIME_PULSE
9
OUT
10
IN_SEL
11
REF_OUT
12
RC
14
IC49
C355
R287
SJ5
3
1
2
R288
C356
R289
C357
R290
C369
FI5_HB30
CAP2[0]
Frequency out
J1708
Misc I/O
Appendix E

Control Card Layout
Top components
Bottom components
Layer 1 (Top)
Layer 2
Layer 3
Layer 14
Layer 15
Layer 16 (Bottom)