

Design of the Electronics for a Small Size League Robot

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Declaration

This is to solemnly declare that I have produced this paper all by myself. Ideas taken directly or indirectly from other sources are marked as such. I am fully aware of the legal consequences of making a false declaration.

Mannheim,

Abstract

Joining the RoboCup Small Size League has become very difficult as new teams need to build their own robot, including the electronics, from scratch. To overcome this issue, this paper covers the problem of creating highly complex electronics for controlling a four-wheeled SSL compliant bot.

It starts with an investigation of the requirements and explicit rule restrictions and then continues with the documentation of the electronics from the TIGERS Mannheim.

All areas for a successful robot control are mentioned in this paper, including the main parts like the primary processor, motor control, wireless communication and ball kicking circuits as well as voltage and current monitoring. Furthermore, some special sensors and interfaces like accelerometers, USB and SD Card connections are mentioned.

To provide enough power for a magnetic kicking mechanism, two circuits are outlined that allow a capacitor bank to be charged to 200V. The explanation of the kicking board continues with a description of additional sensors to enhance the safety in a high-voltage system.

Finally, special topics are discussed, for example the power supply and low-noise ADC supply stages. To round out the paper and to provide a starting point for new teams, all schematics from the TIGERS Mannheim robot are attached.

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List of Abbreviations

ADC	Analog Digital Converter
ARM	Advanced RISC Machines (Limited)
BLDC	Brushless Direct Current
CLDPS	Connectionless DECT Packet Service
COM	Serial Port
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
DC	Direct Current
DECT	Digital Enhanced Cordless Telecommunications
DMA	Direct Memory Access
EC	Electronically Commutated
ESR	Equivalent Series Resistance
FPGA	Field Programmable Gate Array
GBP	Gain Bandwidth Product
GDB	GNU Debugger
GNU	Gnu is Not Unix
I ² C	Inter-Integrated Circuit
IDE	Integrated Development Environment
IGBT	Insulated Gate Bipolar Transistor
ΙΟ	Input/Output
IR	Infra-Red
JTAG	Joint Test Action Group
LED	Light Emitting Diode
MCU	Microcontroller Unit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NTC	Negative Temperature Coefficient
OP	Operational Amplifier
OpenOCD	Open On-Chip Debugger
PC	Personal Computer

PWM	Pulse Width Modulation
RAM	Random Access Memory
ROM	Read Only Memory
SAR	Successive Approximation Register
SD	Secure Digital (memory card)
SPI	Serial Peripheral Interface
SSL	Small Size League
TCP/IP	Transmission Control Protocol / Internet Protocol
TDMA/CA	Time Division Multiple Access / Collision Avoidance
TIA	Transimpedance Amplifier
UART	Universal Asynchronous Receiver Transmitter
USB	Universal Serial Bus
WLAN	Wireless Area Network
XOR	Exclusive OR

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1 Introduction

SSL suitable robots demand a very good knowledge in circuit technique to build an electronic system that can safely and reliably control all parts of a robot. To simplify the access to the SSL league, this paper describes the electronic system of a robot from the *TIGERS Mannheim*. The discussed electronics has already made it through two development stages and is now at version three. Although there is no perfect solution, this paper tries to put the best ideas (also inspired by other teams) together to build a good robot control platform.

As a starting point for other teams, all schematics are attached to this paper. Every section deals with a special part of the electronics and it can be helpful to follow the schematics while reading.

Furthermore, this paper assumes that the reader is familiar with basic electronics. Microcontroller and bus system like SPI and I²C should be well known. Besides, knowledge about operational amplifiers and ADC functional principles (especially SAR types) is useful. As this paper only provides an overview, every section has several references to datasheets and papers that can help in the understanding of the topic.

1.1 Requirements

For the control of a SSL robot, a locomotion system is necessary. Over the years, it turned out that the mostly used motion system consists of four brushless motors. The Maxon Motors EC45 with 30W of power has become the de facto standard in the league. For the control of the ball, a dribbling mechanism is needed. For this purpose a fifth motor is used, which is also a brushless motor, but has less power. This leads to the first requirement of controlling five brushless motors over all.

A soccer robot also needs a kicking mechanism. This mechanism is a solenoid that is energized by some capacitors. To achieve a high kicking force, the capacitors need to be charged to approximately 200V. Converting the battery voltage to such a high voltage is the second requirement.

For a communication with the central computer, which is controlling the robots, a wireless communication is needed. It should provide enough throughput to receive commands from the computer while simultaneously sending status messages. Furthermore, it should be robust and not susceptible to environmental noise.

To control all parts, a powerful main processor is needed. Due to limited space in the robot, a single processor should handle all tasks needed to control the equipment. Additional hardware interfaces for bus systems and pulse width generation help simplifying the hardware design and reducing processing overhead.

In addition to these primary requirements, several other sensors can help increasing system safety and motion performance.

1.2 Restrictions

Even though there are only few restrictions for the electronics of a SSL robot, they are indeed demanding. The main problem is the size constraint as the robots maximum diameter is 180mm and the height is limited to 150mm. Furthermore, the usage of Bluetooth wireless communication is prohibited. Apart from this, the official rules do not state any further restrictions. [1]

2 System Overview

The main processing unit in the robot is a STM32F103ZE (32-Bit Cortex-M3 core) from the high-density performance line from STmicroelectronics. This microcontroller is clocked with 72Mhz and has 512kB of ROM and 64kB of RAM. Altogether it has 112 IOs available. Besides, it has built in support for SPI and I²C busses as well as for UARTs, SD cards and timers. Together with its two DMA controllers this MCU provides enough performance to control the complete equipment in the robot. [2] gives a good overview of the capabilities of the STM32. [3]

Figure 1 shows an overview diagram containing all parts of the *TIGERS Mannheim* robot equipment. As one can see, the architecture heavily depends on the built-in bus support and other hardware features. All components will be examined later in more detail.

The STM32 has been chosen because it is very well documented and available in stores. Furthermore, it can be programmed with a toolchain consisting only of free-ware tools. This includes, among other things, the Eclipse IDE, the CodeSourcery Lite Toolchain for ARMs and the GNU Debugger (GDB) via JTAG (with OpenOCD). As the programming and debugging of the STM32 would go beyond the scope of this paper, it is not discussed in more detail.



Figure 1 System Overview

3 Motor Control

The control of a brushless motor is more complex than the control of a usual DC motor as the commutation of phases does not happen automatically. In a DC motor, the stator consists of permanent magnets and the rotor is made of coils being energized. As the coils are energized, the rotor starts to turn and the commutation starts.

A brushless motor has a rotor with permanent magnets and the stator is made of coils. This has the advantage of eliminating brush sparking and increasing the lifetime of a motor. As this motor does not commutate automatically, a controlling logic is required, which handles the commutation. For this reason, a brushless direct current motor is sometimes also called an electronically commutated motor.

Most BLDC motors consist of three coils which are connected together in a star configuration. Thus, a motor has only three connections. With three coils and one pair of poles in the rotor there is a total of six phases which need to be processed in the correct order. To know which phase has to be set next, some motors (like the ones used here) are equipped with hall sensors. As these sensors have a digital output, the next phase can easily be determined. More information on this topic can be found in [4].



Figure 2 BLDC control schematic

To control the motor, all three phases must be able to be set to ground or supply potential. This is done with half-bridges. Each half-bridge consists of two transistors (mostly MOSFETs). A half-bridge can either be made of two N-channel MOSFETs or a

complementary pair of one N-channel at the low side and a P-channel at the high side. In a complementary connection, the drains would be connected together and lead to the motor.

Figure 2 shows three half-bridges in a dual N-channel configuration (note the freewheeling diodes). This configuration has the advantage of low on-resistance $R_{DS,on}$ and thus low power dissipation.

A certain problem arises with enabling the high-side MOSFETs in such a configuration. A MOSFETs conducts if the voltage at the gate exceeds the gate to source threshold voltage (G_{th}). This fact requires the voltage at the high-side gate to rise above the supply voltage to enable the MOSFET. As the supply voltage is most often the highest voltage available, a bootstrapping circuit is used as a charge pump to provide a voltage above the supply voltage. The capacitor in the bootstrapping circuit will constantly lose its charge due to leakage currents. That means that the high-side MOSFETs cannot be turned on for an indefinite time. As this is also a very uncommon state for a motor, it should not be a problem to avoid this issue. The capacitor in the bootstrapping circuit should be big enough to conduct for a complete PWM cycle.

For the robot, a complementary half-bridge would also be possible and has the advantage of an easier control of the high-side MOSFETs. Its disadvantage is the higher on-resistance which will lead to higher power dissipation.

Phase	HA	LA	HB	LB	HC	LC
1	1	0	0	1	0	0
2	1	0	0	0	0	1
3	0	0	1	0	0	1
4	0	1	1	0	0	0
5	0	1	0	0	1	0
6	0	0	0	1	1	0

Table 1 shows a sequence to rotate the motor in clockwise direction. The selection of the phase is done with the hall sensor input.

Table 1 Commutation sequence, clockwise

For the speed control of the motor, three different modes of PWM generation can be used. As an example, a PWM generation for phase 1 will be examined.

Normal PWM generation is done by enabling HA and LB during the on-time and disable both during the off-time. This is the easiest mode and also the one with the highest power dissipation. As current through an inductor (motor) cannot stop suddenly, it must flow over the freewheeling diodes built into Q2 and Q3. This current flow heats up the MOSFETs.

The second mode is called passive freewheel. In this mode, HA and LB are enabled during the on-time (as in normal mode). During the off-time, LB stays on and thus provides a way for the current to easily flow to ground. This eliminates the losses at Q3 from the previous mode.

The third mode is active freewheel. Like in the other modes HA and LB are enabled during the on-time. In the off-time LB stays on and additionally Q2 is turned on. A current will still flow from ground to coil A, but this time not over the diode in Q2, but over the MOSFET itself. As the MOSFET has a much lower resistance than the diode, overall losses are reduced to a minimum. Table 2 summarizes all modes.

Mode	PWM	HA	LA	HB	LB
Normal mode	ON	1	0	0	1
Normarmode	OFF	0	0	0	0
Passive freewheel	ON	1	0	0	1
	OFF	0	0	0	1
Active freewheel	ON	1	0	0	1
	OFF	0	1	0	1

 Table 2 PWM generation modes (Phase 1)

The active freewheel mode has an important exception as it is shown in the table. It switches between HA and LA. It is obvious that both MOSFETs should never be enabled together, as this will lead to an instant short-circuit situation (shoot-through condition). Even if active freewheel does not enable them both by design, it may happen that Q1 is already conducting while Q2 is not disabled and vice versa. This is due to the fact that a MOSFET starts to conduct if its gate voltage is above the gate to source threshold, which is always lower than the supply voltage. To prevent this situation, a dead time should be inserted between disabling HA and enabling LA, so that no shoot-through condition can occur.

Summarized, is the active freewheel mode is, together with an appropriate dead time, able to control very large currents without significantly heating up the MOSFETs.

For high frequency PWM, a MOSFET driver is necessary to quickly transfer the gate charge. The robot uses a fully integrated driver for 3 half-bridges, the IR2130. This driver has several important features. First of all, it does not allow both MOSFETs of one bridge to be enabled. If its inputs detect such a signal, the output is inhibited. Furthermore, it has a bootstrapping capability for the high-side N-channel MOSFETs and an automatically inserted dead time if switching both MOSFETs of one bridge. With an external shunt resistor to ground, a built-in operational amplifier and a voltage comparator, it also features a way of disabling the outputs if the motor consumes too much power. An active low "fault" output can be used to drive an LED and indicate the failure to the user. Furthermore, the driver converts the 3.3V logic level input and does not put any load on the MCU. [5]

All in all, this driver is ideally suited to drive dual N-channel half-bridges in active freewheel mode with enhanced safety.

3.1 Encoders

To provide an accurate feedback for the MCU in controlling the motors, an incremental rotary encoder is attached to the wheel axis. The E4P encoder from US Digital has a resolution of 1440 pulses per round. This resolution allows the MCU to execute the control algorithm with a frequency of 100Hz.

The encoders are attached to all driving motors; the dribbling motor is not equipped with an encoder. The outputs of the encoders are two square waves which are 90 degree out of phase. Depending on the leading rising edge, the motor either turns clockwise or counter-clockwise. The STM32 helps in interfacing these encoders by providing a timer input mode that handles exactly such a signal. Although four timers are used for all driving motors, this usage greatly reduces the coding overhead for manually processing such signals. Without this timer capability, the STM32 could not be used stand-alone for such a robot.

3.2 Current Monitoring

For additional safety and monitoring purposes, the current of all motors can be acquired. This is done via a low side shunt resistor and an additional operational amplifier stage. The signal from the OPs is then fed into an Analog-Digital-Converter (ADC) which samples the applied voltage. The used ADC for this purpose is a 12-bit SAR type with an I²C interface (AD7991). In theory this ADC can sample more than 150kSPs at high-speed mode. As the STM32 is only capable of normal and fast mode, the throughput is much lower; moreover the actual request rate will be around every millisecond. This is still enough for a safe monitoring [6].

If the current of a motor should exceed a programmed limit, the motor can be disabled or automatically regulated by the MCU.

3.3 Commutation Interrupt

To guarantee a smooth motor control, it is important to switch to the next phase as soon as the hall sensors change their output. Every motor has three hall outputs. That makes 15 lines which should be checked very often. Again, this implies a heavy load for the MCU. To overcome this issue, the three lines of one motor are logically XORed together. Thus, the lines to monitor are reduced to five. As the hall sensors output a gray code, the XOR lines change if the sensor output changes.

To further reduce processing overhead these lines are wired to external interrupt inputs of the STM32. The STM32 has exactly five external interrupts which have their own interrupt request. This fact helps to significantly reduce the used processor time.

4 Power Supply

The power for the robot is taken from two Lithium-Polymer batteries with two cells each. They are connected in series and thus provide a main supply voltage VCC in the range from approximately 13V to 16.8V if fully charged. Two batteries were chosen because of space constraints in the robot. A single four cell battery could also be used. Within the main electronics, three different voltage rails exist. The battery voltage is directly used for the motors and the kicker charging circuit. Furthermore, a 5V rail exists for powering the motor hall sensors and most of the separate ADC supplies (see also 8 ADC Supply and Filtering). Finally a 3.3V rail is used for the MCU and most of the digital parts.

VCC	5V	3.3V
Motors	Motor hall sensors	MCU
Kicking Device	Encoders	Accelerometers
5V and 3.3V regulators	ADC linear regulators	LED Extension
	Shunt monitors	DECT
	Ball Detection	USB
	Buzzer	SD Card
		UART
		JTAG

Table 3 Supply voltage distribution

The 5V and 3.3V rails are derived from VCC by two LT3480 step-down switching regulators. They output a maximum current of 2A and have a switching frequency of up to 2.4Mhz. In the robot, they are used with a frequency of approximately 350kHz which is a trade-off between external component size (inductor, capacitor) and efficiency. The higher the frequency, the smaller the needed external components, but the efficiency also drops. In a mobile application the efficiency should be as high as possible to achieve a maximum of run-time. The LT3480 has an efficiency of more than 80% over most of its operating range.

On the board the complete circuit for a single step-down is some 15x15mm, including all external components like capacitors and the inductor. The regulator itself comes in a tiny MSOP-10 package which is only 3x3mm in size. For more information on the LT3480 see [7].

For enhanced safety and monitoring, the currents of all supply rails can be observed. This is done via a shunt resistor in the respective high-side trace. A high-side shunt was chosen because it is much easier to integrate as a low-side one. A low-side shunt resistor to ground would need to split the ground signal of the components and thus would influence the supply voltage as the voltage drop above the shunt-resistor rises. As a high-side shunt is not referenced to ground, it is hard to measure because only very few operational amplifiers have an input that is allowed to rise to VCC (max. 16.8V). A further handicap is the voltage offset. To solve this issue the INA139 current shunt monitor is used.



Figure 3 INA139 shunt monitor [8]

Figure 3 shows that the INA139 is essentially a differential amplifier that converts the voltage above R_s to a current and outputs it on OUT. With a resistor R_L to ground this current is converted back to a voltage, and it is also amplified by a certain factor. The most important fact is that the voltage is now referenced to ground with no offset. That makes it very easy to be fed into an OP and then into an ADC. [8]

To protect the battery it is useful to observe the cell voltages. This is especially important as Lithium-Polymer batteries are very sensitive to deep discharge and can easily be damaged if discharged below 3.2V. As the cells are connected in series, they cannot be measured individual. Lithium-Polymer batteries usually have connections to all cell connection points. This can be used calculate the voltage of an individual cell.



Figure 4 Cell voltage dividers

In Figure 4 the voltages are first reduced by four voltage dividers. Table 4 shows the voltages of a fully charged battery and the divider factors.

Cell	Voltage (max)	Divided by	Result (ADC _i)
1	4.2V	2	2.1V
2	8.4V	4	2.1V
3	12.6V	6	2.1V
4	16.8V	8	2.1V

Table 4 Cell	voltages
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Now the voltage can safely be amplified by an OP and measured with an ADC. The measured results can then be used by the MCU to reverse the calculation and get the single cell voltages. For example for cell 2 this would be:

$$V_{c2} = ADC_2 \cdot 4 - ADC_1 \cdot 2$$

All voltages from the battery and the shunt monitors are fed into OPs, which are configured as impedance converter, and then into an AD7998 ADC. This ADC has 8

inputs and an I²C interface [9]. Like the AD7991 used for the motors, it can achieve transfer rates of more than 150kSPS, but for monitoring purpose it is only queried twice per second.

5 Kicker

For the kicking solenoid, a bank of capacitors needs to be charged. In the robot, four 1200μ F capacitors are connected in parallel. That makes an overall capacity of 4800μ F. For a powerful kick, this charge needs to be transferred as fast as possible to the solenoid. The VCC rail cannot provide the needed voltage for such a fast transfer. As a solution, the capacitors need to be charged to some 200V. Several methods exist to achieve this conversion.

The easiest way is to use a step-up converter as it is shown in Figure 5.



Figure 5 Step-up converter circuit

To achieve a usable charge time of a maximum of 10s, the currents in this circuit will most likely destroy the inductor and the diode. With a 50% PWM duty cycle the currents are approximately 8A at the diode. The initial peak currents with an empty capacitor C8 are above 200A. These results were taken from an LTSpice simulation. It is obvious that these currents will destroy the circuit.

Another option is a flyback converter circuit. Its most important part is a line output transformer, which transfers its charge from the primary winding to the secondary winding when the MOSFET Q7 is switched off. An example circuit is shown in Figure 6.



Figure 6 Flyback converter circuit

This circuit has the additional advantage of being galvanically isolated. This is especially important as the circuit is directly connected to the mainboard. Furthermore, the nominal current above the diode is only 2A. Peak currents with empty capacitors are only around 30A. On the primary side the current is around 7A. The current peaks can further be minimized if the PWM duty cycle is reduced to 5% at the beginning. The circuit is inspired by the example circuit in the LT3750 datasheet [10]. The LT3750 can be used to load the capacitors automatically. Due to the lack of controlling the PWM frequency from the MCU the base circuit has been used, but without the LT3750 itself. With a constant duty cycle of some 10%, the capacitors are charged to 200V in 30s. The duty cycle can be increased when the voltage above the capacitors rises. With an

optimized duty cycle control, the capacitors can now be charged within 3s to 200V. To monitor the circuit three shunt resistors exist. The current on the primary side is monitored by a 5mOhm resistor. For discharging, two power stages are used, consisting mainly of an IGBT. IGBTs are used because they can withstand high voltages and can switch very high peak currents. The maximum current while discharging over a 1mH, 1.20hm inductor from fully charged capacitors is 130A. Measuring this current cannot be done over a discrete shunt resistor as the power dissipation will destroy this resistor. To overcome this issue, a conductive path on the PCB has been used with an intentional resistance of 10mOhm. This path is 53mm long and 2.54mm wide (standard 35µm copper height). It is important to watch the increase in temperature because this path

copper height). It is important to watch the increase in temperature because this path will also dissipate power. The temperature change can be approximated with the following formula [11].

$$K_{Cu} = 4.886 \cdot 10^{-3} \frac{K \cdot mm^4}{A^2 s}$$
$$\Delta T = K_{Cu} \cdot I^2 \cdot \frac{t}{h \cdot w}$$

with path height h, path width w and pulse current I over time t.

A full capacitor discharge is approximately 33A for 25ms. With these values and the formula above, this heats up the shunt path by 17.1°K. Real tests showed that the actual heat up is about 5°. This can be put down to the fact that the heat is distributed over the epoxy board.

Beside the shunt resistors, a voltage divider is used to scale the capacitor voltage down by a factor of 100. To further monitor the board, NTC resistors have been placed between the shunt conductive paths to observe the temperature.

All voltages are then fed into an OP stage followed by an ADC. The ADC78H89 from National Semiconductor is a 7-channel SAR ADC with 12 bit resolution. It has a SPI interface and can sample with up to 500kSPS [12]. The SPI transfer has been chosen as it is the fastest one available in the MCU. Together with DMA control the ADC could be sampled with maximum speed. This is only useful for testing purposes, e.g. taking a measurement of the discharge current. In the robot the results are polled less frequently. The data from the ADC, especially the capacitor voltage, can be used to control the

charge PWM duty cycle. The flexible PWM frequency ranges from 60kHz to 500kHz with duty cycles from 5% to 66%.

All in all the flyback converter circuit has proven to be stable and fast. With additional stress tests, the charge time could be reduced further. Although the board is bigger than the capacitor charge boards of other SSL teams, it has the advantage of superior monitoring and safety options.

5.1 Ball Detection

The ball detection mechanism consists of two parts. The first one is a single infrared light barrier mounted in front of the dribbler. This light barrier is responsible for detecting a ball in kicking range. Beside this light barrier, three other infrared senders and receivers (IR diodes), with daylight blocking filter, are mounted above the dribbling bar. These IR LEDs should be able to measure the ball position in horizontal direction.

The robot can then determine if the ball is centred before the kicker or if it is offset to the left or to the right.

Figure 7 is a picture of the top side of the ball detection board. The three IR LEDs and receivers are paired above each other.



Figure 7 Ball detection board layout

With this configuration, it should be possible to calculate the ball position by triangulating the received light strength. All IR senders are controlled individually.

The IR receivers are simple IR diodes. In contrast to other IR sensors, they react very fast to a change of IR light. Their drawback is their small signal output. Usually the output is around some micro Ampere. The best way to amplify such a signal is via a transimpedance amplifier (TIA).



Figure 8 Transimpedance Amplifier circuit

Figure 8 shows the basic circuit for a TIA. The operational amplifier is trying to pull its negative input to virtual ground. This is done via a large feedback resistor which converts the small current from the diode to a voltage. The diode is used like a solar panel in this configuration. The capacitor is used to prevent the circuit from oscillating. [13].

The output from the TIAs is directly fed into an ADC. The ADC is an AD7994, 12-bit SAR type with I²C interface. This ADC has some special features like high and low limit registers that can trigger an alert line if the conversion result violates these limits. This is very useful in pass playing. If the main light barrier is interrupted, the alert output changes and can trigger an interrupt at the MCU [14]. The IR senders are triggered over simple transistors. They tolerate pulses of up to 100mA for short times. This can be useful if they are used in PWM mode and if additional IR power is required. The TIA is used as it provides a good bandwidth in comparison to other evaluation circuits. Depending on the resistor and capacitor values (and the GBP of the OP) the bandwidth can be several 10kHz.

6 DECT

For the communication with the central computer a DECT wireless connection is used. The DECT technology is usually used in cordless phones, but it is also capable of transferring data packets. The DECT frequency is 1.9Ghz. Using DECT has several advantages compared to WLAN communication. First of all WLAN is in the frequency range of 2.4Ghz and very widely used. Furthermore WLAN uses CSMA/CA which results in very unpredictable and sometimes very long transfer times (>50ms). In a fast dynamic robot soccer game such latencies are too long for a good control.

DECT uses another approach in media access control. It uses TDMA/CA. This method defines multiple time slices and every client gets a defined slot in a time frame. With this method the latency becomes predictable as the assigned time slot remains fixed.

To simplify the usage of DECT for a robot a fully integrated module from the company Höft & Wessel is used. The HW86012 module combines the complete logic for demodulating the received data and interpreting packages. The module has a size of 52x37mm and can be mounted on top of the main board [16].

For packet oriented data transfer Höft & Wessel invented the CLDPS wireless transfer method. HW states that the original DECT packet service DPRS has several drawbacks which makes it almost impossible to use [17].

The modules microprocessor also implements a TCP/IP server on top of the CLDPS service [15]. This makes it easy to communicate with the robot from a computer application. The TCP/IP packets are examined by the module and the payload is transferred via a UART connection to the MCU. The STM32 has built-in hardware support for UART communication and thus makes it easy to communicate with the module. For the communication unicast packages are used to address each robot individually. Figure 9 illustrates the communication process.



Figure 9 DECT communication

7 Miscellaneous Sensors and Actuators

To further improve the performance of the robot, several additional sensors and actuators are mounted on the main electronics board. Some of them are used for user feedback while others can even improve motion behaviour.

7.1 Accelerometers

Two MEMS inertial sensors are mounted on the top of the main board. The used sensors are LIS3LV02DQ parts from STmicroelectronics. They feature full 3-axis support with a scale of +-2g or +-6g (digitally selectable). The typical resolution at 2g scale and a bandwidth of 40Hz is 1mg. The interface can either be SPI or I²C depending on the external circuit. To reduce wiring efforts I²C is used in the robot. The IC is available in a tiny QFPN-28 package (7x7mm) and can still be soldered by hand if a special land pattern is used. [18]

The output from the LIS3 can be used by the MCU to monitor the real motion of the robot. For this purpose one sensor is mounted in the exact centre of the robot. This sensor is not affected by rotational forces and is primarily used to measure acceleration in the X and Y direction. The second sensor is located 6.5cm away from the centre. It is used to measure rotational acceleration. The sensor will also measure motion on the robots X and Y axes, but in combination with the first sensor these measurements can be compensated.

The Z axis from the sensors is not used for motion control, but can for example be used to detect if the robot has been lifted. As a consequence the motors can be stopped.

It is planned that the sensors aid in motion control by detecting impacts from other robots and automatically correct the own movement. Furthermore, they could be used for calibration purposes.

7.2 UART

One UART port from the MCU is available for direct connection to a PC. This interface is very useful for first-touch experiences with the MCU because it is an easy way to output data on a terminal or send data to the MCU. It can also be used for debugging output.

To fully comply with the RS-232 standard a level shifter is used. The MAX3232 is used to convert the logic level of the MCU (0-3.3V) to the standard voltage of +-12V. [19]

The UART can then directly connected to a PCs COM interface. A simple terminal program (like PuTTy) can be used to communicate with the MCU.

7.3 Buttons and LEDs

For direct user input and feedback the remaining IOs from the MCU are connected to buttons and LEDs. Two LEDs are directly connected to the MCU. They can be used to indicate an OK or FAIL status if other reporting methods are not available (e.g. damaged UART or DECT). Two push buttons are provided and can be used to stop the motors or to discharge the kicker (depending on firmware). A third button is reserved for resetting (restarting) the MCU.

7.4 Buzzer

A piezoelectric buzzer is mounted on the main board to provide some audible feedback. If the cover is mounted on the robot it is not possible to see the LED indicators. The buzzer can be used to signal some failure status and draw the user's attention to the robot.

7.5 LED Extension

To have a more accurate status reporting without having to watch the central computer or UART output, some more LEDs have been mounted on the main board. Eight additional LEDs are controlled by a PCF8574 port expander [20]. This expander has eight open-drain outputs which are attached to LEDs. It is controlled via an I²C interface and can thus easily be integrated in the existing bus architecture.

7.6 SD Card

The MCU has built-in support for a SD card interface. A micro SD card slot has been mounted on the main board to use this feature. The SD card might be used to store additional working parameters or for logging purposes. The MCU interface provides real four bit data width and DMA control for the card interface. It should thus be no problem to implement an effective logging mechanism.

7.7 USB

A USB interface is part of the MCUs built-in interface support. As it requires very few external components it has been added to the main board features. Currently a serial device is emulated via the USB connection. Like the UART this communication can be used to interface terminal applications. The advantage over the UART is the USB connection. Most notebooks these days do not provide a COM interface, but multiple USB connections. The USB connection can then be used for example to configure the DECT module.

7.8 JTAG

For programming and debugging a standard JTAG interface is used. The JTAG interface is a 20-pin IDC connector. It is connected to an OpenOCD USB adaptor, which is used for programming. Via JTAG the MCU can also be debugged during runtime from a PC. The JTAG interface is part of the Cortex-M3 core and requires very few external components.

8 ADC Supply and Filtering

The robot electronics uses several ADCs to convert data from various sensors. To achieve a good performance and eliminate noise, input and supply filtering is essential. Figure 10 shows a standard circuit for input filtering. The input first passes a RC filter. The values of the RC filter depend on the input. High values can also be used to build an average of the input signal. This is useful if PWM signals are measured. The OP is also used to convert the high impedance input to a low impedance output. It can additionally be used to amplify the signal. The shown configuration is non-inverting amplifier, but other configurations are also allowed. The output of the OP is then again RC filtered. The second filter usually has a much higher bandwidth than the input one.



Figure 10 ADC input filtering

For the ADC it is important to have a low impedance source. SAR ADCs need this low impedance to charge the internal sample and hold capacitor. If the input impedance becomes too high, the capacitor cannot be fully charged and the conversion result is useless. The small capacitor C16 aids in providing the needed charge.

Filtering the input signal is one way to improve the ADC accuracy. Another option, which is sometimes underestimated, is filtering the supply voltages and providing a clean reference input. The output of a switching regulator usually has a ripple of several mV. This ripple distorts the output of the OP and the ADC. For a good supply, it is recommended to use a separate linear regulator. Linear regulators have higher power dissipation as switching regulators but they output a signal with very low ripple. Figure 11 shows a circuit for a good OP and ADC supply. The used regulator is a LP2980 from National Semiconductor. It provides a maximum output of 50mA and is available in a tiny SOT23-5 package. Furthermore it only requires a single external capacitor. The

capacitor should have a value of 10μ F and an ESR of 0.1 to 10 Ohm [21]. A tantalum capacitor is the ideal solution for these requirements.



Figure 11 ADC supply filtering

The linear regulator already outputs a good 3.3V signal. From a single regulator the supply for the OP, the ADC and the reference voltage is derived. To isolate the components against each other, every supply is additionally filter by an RC element. The resistor value depends on the current consumption of the component and the allowed voltage drop above the resistor.

Most ADCs have an input for a reference voltage. The conversion range is then scaled from 0V to the reference voltage. A 2.048V reference is very useful as it results in a resolution of 0.5mV per Bit (12 bit ADC). The reference voltage is usually very low loaded. To keep component size low, a simple zener diode can be used as a reference source. It is additionally bypassed by a 10μ F tantalum and 100n ceramic capacitor. In summary, it can be stated that such a circuit increases the effort for a voltage supply but also results in superior OP and ADC performance.

9 Summary

With this paper the fundamental problem for new teams of "How to make a SSL robot electronics" is covered. It acts as a starting point and is feature-packed with additional interfaces and sensors. The list of references can be used to gain further knowledge in the design of robot electronics.

The paper showed that it is possible to control the complete robot equipment with a single processor. A further advantage of the Cortex-M3 over a FPGA solution is its easiness of programming. A user that is familiar with C should not have a problem to take on microcontroller programming. With 512KB of flash even very big programs can be put on the microcontroller.

The motor control circuit has unique safety features such as shoot-through prevention and over-current protection. Furthermore it supports boot-strapping to use a dual Nchannel configuration in a half-bridge. Together with the active freewheel control mode power losses can be reduced to an absolute minimum.

The kicker circuit is equipped with several sensors and can already charge a 4800μ F capacitor bank to 200V in 3s. As it is build around a line output transformer, it provides an isolated high-voltage area.

Other features complete the latest mainboard version. The DECT module provides a good and easy network interface for the robots. The power supply has an efficiency of over 80% and helps to prolong battery life. Additional sensors and interfaces can increase motion performance and provide enhanced safety.

At the time of writing this paper the predecessors of the mainboard (v1 and v2) were used to experiment with all circuits and to gain knowledge about motor and kicker control. The presented schematics and all information of this paper are related to version 3 of the mainboard.

In the future the new boards are produced and tested in a competitive environment. Due to the experience made with the previous versions these boards are expected to be robust and stable. Furthermore the currently unused sensors like the accelerometers will be used to implement an additional motion control loop. With these entire enhancements the *TIGERS Mannheim* SSL robot is expected to be very competitive.

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B Schematics





























