Design and construction of electronic control unit

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Abstract

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The main objective of this project was to create a new, future-proofed, electronic control unit for a test station at GE Healthcare in Uppsala. The control unit was to be created in cooperation with the technical consultant firm Rejlers.

The project consisted of two parts, one investigation part and one design part. The investigation part consisted of examining the previous control unit and its connection between the quality control station and the host computer. This examination resulted in a specification of requirements which was used as a basis in the design of the new control unit. The design part consisted of finding durable and reliable components that met the specification of requirements. During the design process the work was documented and compiled in a technical documentation for the control unit.

The project resulted in a new control unit that was improved by using a programmable logic controller that was directly compatible with LabVIEW, moving external power supplies inside the control unit to limit the number of cables and adding cartridge fuses for safety. It also resulted in a full technical documentation of the unit, facilitating future maintenance.

The new control unit was considered to be future-proofed, but in order to consider the entire test station future-proofed the quality control station would have needed to be replaced as well.

At the time this report was written, the new electronic control unit had been designed and was under construction.
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Chapter 1

Introduction

1.1 Background

The electronic control unit was a part of a test station at General Electric Healthcare (GE Healthcare). The test station was used to quality control a specific part used in medical equipment for protein analysis. The control unit’s objective was to control the QC station where the examined part was placed during the quality control. Finding spare parts for the control unit was a struggle since some of the parts were no longer in production as well as industry standards had changed over the last years. The down time of the machine was costly as production was halted and prolonged by delivery times of spare parts, this demanded a new unit to be constructed.

1.2 Objective

The objective of the project was to design and implement an electronic control unit and create a well documented specification for it. The production of the unit was performed in cooperation with the technical consultant firm Rejlers AB.

The aim of the project was to future-proof the electronic control unit and improve the solutions from the previous one. That included analysis and understanding how the previous control unit worked, as well as investigating the possibilities of improvements for the QC station. Future-proofing meant that components were chosen with the aspect of securing availability of spare components in the nearby future. This would facilitate future maintenance, as well as improve the life expectancy of the control unit.

1.3 Limitations

Components would not be ordered by Rejlers before a complete solution was produced, thus the entire control unit had to be designed in theory. Rejlers would construct and implement the new control unit in consultation with us when the complete design was approved. The selection of components for the the control unit was limited by the hardware to be controlled inside the QC station. The project was time limited to the 15 credits distributed over the spring semester of 2018.

1.4 Notation

Due to some information about the control unit and its functions being classified, certain information has been omitted from this report. Throughout this report all voltages is referred to positive DC voltage unless stated otherwise.
Chapter 2

Theory

2.1 DC motor control

The direct current motor is well used in all type of applications, industrial as well as commercial. A benefit of the DC motor is that the speed can be controlled by simply varying the applied voltage. The DC motor has also a simple and rugged construction which leads to longevity [1]. There are different types of DC motors with different constructions and applications. One of them is the permanent magnet DC motor where the field windings has been replaced with permanent magnets and the armature current is supplied via conducting brushes to the rotor. To fully rotate the rotor shaft the polarity of the applied voltage over the rotor windings is switched using a commutator. To operate the motor in reversed direction the polarity of the supply voltage is switched, this type of motor is called bidirectional [2].

2.1.1 H-bridge

An H-bridge is a common way to control a bidirectional DC motor when only a unipolar power supply is available. By switching the polarity of the supply voltage using transistors or MOSFETs, depicted as switches in Figure 2.1, the DC motor can be driven in two directions [3]. Closing the switch to V+ of the supply voltage on the “positive” side of the motor and simultaneously closing the switch to V- on the “negative” side gives the motor a positive voltage, left circuit in Figure 2.1. Closing the switch to V+ on the “negative” side and closing the switch to V- on the “positive” side gives the motor a negative voltage, right circuit in Figure 2.1. It is important that the switches located on the same side of the motor are not closed at the same time as this would result in a short circuit. To avoid this, the control signal is often driven through an inverter.

![Figure 2.1: H-bridge motor control.](image)

2.1.2 Flyback voltage

Flyback voltage occurs when the switch controlling a supply voltage is opened, interrupting the current to an inductive load such as a DC motor, see Figure 2.2. The voltage over an inductor is dependent on the change in current according to

\[ V_L = -L \frac{di}{dt}, \]
where $V$ is the induced voltage [V], $L$ is the inductance [H] and $i$ is the current through the inductive load [A]. An abrupt interruption of the current will force a voltage to be induced with an opposite polarity to the voltage supply. The flyback voltage can damage a mechanical switch by creating an arc across the contacts [4] causing pitting and burning which shortens the lifespan of the contacts. If a solid state relay is used the flyback voltage can create an avalanche breakdown where the conducting electrons are accelerated to high enough speeds to knock other bound electrons free causing high currents [5]. An avalanche breakdown will permanently damage the pn-junctions, which are the conducting parts of the solid state relay.

![Diagram of flyback voltage](image.png)

Figure 2.2: Occurrence of flyback voltage.

To suppress the flyback voltage a diode can be placed in parallel with the inductive load. When the switch is opened the load discharges its stored energy as a current that flows through the diode, protecting the switch. A single diode can be used if the power supply is unipolar, however if the power supply is bipolar a varistor or two diodes mounted in series with opposite polarity needs to be used instead.

### 2.2 Sinking and sourcing outputs

As DC devices can be connected two ways to a programmable logic controller (PLC), the outputs must be chosen to be either **sinking** or **sourcing**. The sinking output allows current to flow into the PLC and the sourcing output allows current flowing in the opposite direction out from the PLC. Choosing the wrong type of output may damage the components and result in a malfunctioning circuitry. When either output is open they are left floating with undetermined potential. [6].

![Diagram of sinking and sourcing outputs](image.png)

Figure 2.3: Sinking and sourcing outputs.
2.3 Driving LEDs

An LED is a special type of semiconductor diode that emits light when activated. It is made by doping a semiconducting material with impurities to create one region with free positive charge (p-doped) and one region with free negative charge (n-doped) [7]. The doping gives rise to a boundary region between the p-doped region and the n-doped region. This boundary region is then reduced in width when a voltage is applied causing free negative charges (electrons) to pass into the p-doped region. When the electrons lose energy and fall back to the low energy state they often emit photons (light). The color of this light is determined by the electronic band structure of the semiconducting material used [8]. Because the LED has an almost constant voltage drop the number of electrons that emits light can be controlled by a resistance in series with the LED. The intensity of the light is then determined by the current through the series resistance.

2.3.1 Linear regulator circuits

Linear regulators is a cost-effective way to control LEDs. The linear regulator belongs to the family of active regulators, other kind of active voltage regulators are switching regulators and silicon controlled rectifiers (SCR regulators). They all have in common that they employ at least one transistor or operational amplifier (op-amp) to regulate the output voltage. The name linear regulator comes from the component using the transistor’ and op-amp’s linear regions of operation. Among the active regulators the linear regulator is the simplest, it has an advantage in not giving rise to any electromagnetic radiation but it also has a disadvantage in being inefficient due to heat losses [9]. Linear regulators are step-down regulators only, which means that the output voltage can not be higher than the input voltage. In Figure 2.4 the basic linear regulator circuit is shown.

![Linear regulator circuit diagram.](image)

From Figure 2.4 the output voltage from the regulator, $V_{OUT}$, can be derived. The op-amp will regulate its output voltage in order to make the voltage at its inputs equal. This means that the voltage at its positive input, $V_{REF}$ in Figure 2.4, will be equal to the voltage at its negative input. The voltage on the negative input is given by the voltage divider of $R_1$ and $R_2$,

$$V_- = V_{OUT} \frac{R_2}{R_1 + R_2}.$$

Setting these equations equal yields
\[ V_{\text{OUT}} = V_{\text{REF}}(1 + \frac{R_1}{R_2}). \]

The last equation shows that the output voltage is only dependent on the reference voltage and the values of the resistors. With a linear regulator where the reference voltage is set on the ground pin the output current can be controlled by feeding the output voltage back to the ground pin through a resistor and a potentiometer in series. A figure of this circuit is not shown here. When the resistance of the potentiometer changes the regulator will try to keep the voltage difference between the output and the ground pin constant by increasing or decreasing the output current.

### 2.3.2 Buck converter circuits

The buck converter is a DC to DC converter of the type switched-mode power supply (SMPS). The key components of the buck converter are an inductor, a diode and a switch, which can either be an insulated-gate bipolar transistor (IGBT) or a metal oxide semiconductor field effect transistor (MOSFET). To smoothen the output voltage a capacitor is often added on the output. In basic operation the inductor stores energy when the switch is closed and when the switch opens the current through the inductor flows through the diode instead of the switch meaning that the inductor works as a voltage source, see Figure 2.5. If the current in the inductor never reaches zero the buck converter is said to be operating in continuous current mode [10], in discontinuous current mode the current reaches zero. An advantage of buck converter circuits is their ability to store energy making them more efficient than for example linear regulator circuits.

![Figure 2.5: Basic buck converter circuit diagram.](image)

Buck converters come in versions where the output current is controlled instead of the output voltage. By setting different switching intervals for the switch the current through the load can be controlled. These intervals can be set using pulse-width modulation (PWM) or by using a current sensor and letting the switch regulate itself to achieve the desired current is achieved. When the component regulates itself a nominal current can be set which can then be controlled by setting a voltage on an adjusting pin. A voltage divider with a resistor and potentiometer can be used to vary the voltage on the adjusting pin.

### 2.3.3 LED drivers

A simple way of controlling LEDs is through an LED driver. LED drivers are units made to work as the power supply to arrays of LEDs or specific LED devices and come in a variety of different models. They can either have a constant voltage output, usually 10 V, 12 V or 24 V, or a constant current output, usually 350 mA, 750 mA or 1 A [11]. Most drivers are made to provide a constant output current, but there are also
dimmable drivers available. By using a dimmable LED driver the output current can be controlled thereby controlling the intensity of the LED [12].

2.3.4 Pulse-width modulation

In order to convert one level of DC voltage to a lower level of DC voltage the method of PWM can be used. The voltage is switched on and off at a high rate, during this switching the circuit will experience the average voltage of the pulsed wave, see Figure 2.6. By varying the duty cycle of the pulse, the experienced voltage will change. Common use of PWM is motor control and dimming of LED lights. [13]

![Figure 2.6: Pulse-width modulation.](image)

2.4 Thermal dissipation

As the electric components are not ideal some power will be dissipated as heat. An increase in temperature could reduce the components efficiency. Electronic components’ life expectancy is said to be halved for every 7 °C rise in temperature [14], thus it is of great importance of keeping the temperature low. To calculate the convection from a component to air, Newton’s law of cooling can be used,

\[
\dot{Q} = hA(T_{\text{obj}} - T_{\text{air}}).
\]

(2.1)

\(\dot{Q}\) is the dissipated power [W], \(h\) is the heat transfer coefficient [Wm\(^{-2}\)K\(^{-1}\)], \(A\) is the unobstructed surface area of the object [m\(^2\)], \(T_{\text{obj}}\) is the surface temperature of the object that convects heat [K] and \(T_{\text{air}}\) is the temperature of the surrounding air [K] [15]. \(h\) is typically in the range of 2-25 Wm\(^{-2}\)K\(^{-1}\) for free convection of gases [15]. In order to calculate the thermal conductivity of the walls of an enclosure, Fourier’s law of thermal conductivity is used,

\[
\dot{Q} = \lambda A \frac{T_{\text{in}} - T_{\text{out}}}{\Delta x}
\]

(2.2)

where \(\dot{Q}\) is the dissipated power [W], \(\lambda\) is the thermal conductivity coefficient of the material [Wm\(^{-1}\)K\(^{-1}\)], \(A\) is the unobstructed surface area of the object [m\(^2\)], \(T_{\text{in}}\) is the temperature inside of the object [K], \(T_{\text{out}}\) is the temperature outside of the object [K] and \(\Delta x\) is the material thickness of the object [m] [15].

2.5 Power and losses

Electrical active power is the rate at which electrical energy is produced or consumed and is given by

\[
P = VI,
\]

(2.3)
where $P$ is the electrical power [W], $V$ is the voltage [V] and $I$ is the current [A] [16]. When a current flows through a component with resistive properties some of the energy is dissipated as heat. This power loss is given by Joule’s law of heating

$$P_{\text{loss}} = I^2 R,$$  \hspace{1cm} (2.4)

where $P_{\text{loss}}$ is the power lost as heat [W], $I$ is the current through the component [A] and $R$ is the resistance of the component [Ω] [16].
Chapter 3

Method

The function of the electronic control unit was at first unknown since there was no documentation available. To produce a specification of requirements for the new box and at the same time document the control unit’s and the QC station’s functions the unit and station were examined. Because the test station was used in production, a spare electronic control unit and QC station were used for the examination. The specification of requirements was compiled based on measurements made on the components and information found in the components’ data sheets (for the specification of requirements, see Appendix A). From this specification of requirements a general idea for the new control unit was made. The idea for the new control unit was presented to GE Healthcare with possibilities for GE to choose between solutions to meet requirements. After getting the idea approved by GE a dialogue with Rejlers was established. From this point on, Rejlers acted as support in the process of designing the control unit and were also in charge of producing it.

Based on the QC stations requirements the components were chosen with focus on determinism and reliability. At first the main functions such as the motor control and LED were treated. Different techniques and solutions were examined in order to find the most suitable solution for the project. As solutions for the main features were solved, the work became more focused on details such as mountings and wiring.

A product description document containing the full solution was created. It contained a complete component list where hardware with pricing was listed. The component list could then directly be used as a purchase order. A functional description were also added to the document. Sketches of the connections between the control unit and the QC station and the physical placement of components inside the control unit were drawn. A circuit diagram of the control unit was created and included in the product description. The product description was sent to Rejlers for approval. Rejlers returned the product description with their thoughts on the solution and modifications were made according to Rejlers’ recommendations. The revised solution was then approved by Rejlers and the responsibility of constructing and implementing the control unit was handed over.
Chapter 4

Technical procedure

4.1 Inside the QC station

The QC station was where the component under quality control was placed and tested. It was a sealed box with a slot and the box consisted of a DC motor, an LED, a gauge and two cameras located inside the QC station. An external light source was also a part of the QC station but as a separate unit. The external light source had fiber-optic arms that guided the light to the QC station.

4.1.1 DC motor

In order to clamp and unclamp the part that underwent quality control in the QC station a DC motor was used. By rotating the motor clockwise and counterclockwise a spring was tensed and loosened, which clamped and unclamped the part. The motor was located inside the QC station and was manually controlled in LabVIEW by an operator. The rotation of the motor needed to be controlled through the control unit.

The motor was inspected physically along with its data sheet to define the voltages, power consumption, currents and rotational angle. The motor was a permanent field DC motor rated at 24 V supply voltage with a nominal current of 30 mA and a maximum current of 250 mA. The motor was rated at 0.22 W and was able to rotate 240 degrees. In order to rotate the motor in both directions, the polarity must be switched.

The discharge flyback voltage that could occur when the motor was switched off, could potentially damage the controlling hardware. The motor was therefore brought to a laboratory for examination. The motor was connected to a laboratory power supply set to 24 V, and the differential probes with an attenuation of 1/100 was connected to the supply cables of the motor and to the digital oscilloscope. Several measurements were made driving the motor and breaking the circuit to induce the flyback peak. The oscilloscope recorded the flyback voltage using the trigger function, saving only the data when the data of interest occurred. As the motor is bidirectional the polarity was reversed and the test was repeated, this to make sure of a constant behavior regarding direction of rotation. In order to dampen the flyback voltage, a varistor was placed in parallel with the motor, Figure 4.1.

![Figure 4.1: Circuit diagram over varistor in parallel with motor.](image)

Figure 4.1: Circuit diagram over varistor in parallel with motor.
The available varistor had a max DC rating of 22 V thus the tests involving the varistor were performed using 20 V as supply voltage.

Another way to dampen the flyback voltage was to place two Zener diodes connected in series with reversed polarity in parallel with the motor Figure 4.2. This would force the energy to dissipate in the diodes. This solution works the exact same way when the motor is driven the opposite direction.

![Figure 4.2: Circuit diagram over Zener diodes in parallel with motor.](image)

Simulations were made in LTspice to verify the dampening effect of the circuit using a sinusoidal voltage signal of 60 V. The chosen Zener diodes had a reverse voltage of 27 V to not interfere with the motor’s power supply of 24 V.

### 4.1.2 Cameras

The QC station held two analog, remote, monochrome, micro head, charge-coupled device (CCD) cameras, capturing the examined object from two different angles. Mounted on the cameras were magnifying lenses for a clearer view of small particles on the object, and the black and white images had a resolution of 570 TV lines which corresponds to approximately 0.38 megapixel. The cameras’ control units were mounted on the lid inside the previous electronic control unit and powered with 12 V, consuming 3.7 W each from an external wall power supply. The cameras were connected to the PC through an IMAQ PCI-1409 frame grabber from National Instruments (NI).

During the investigation it was found that the analog cameras were no longer available on the market as they have been replaced with modern digital cameras with interfaces such as GigE Vision and USB3 Vision (which was the official standard for the USB 3.0 interface when used in the image processing industry). The modern cameras would be easier to implement as they did not necessarily require a frame grabber and thus could be directly connected to a computer or a PLC with GigE Vision or USB3 Vision interface. This could result in more convenient programming and less components.

As replacement cameras, new remote micro head cameras with digital interface were looked at in order to fit the existing construction of the QC-station. In general, the remote head micro cameras where expensive relative to its performance and seemed to be replaced in the manufacturers’ assortments with other types of micro head cameras. These new micro head cameras, supplied by manufacturers such as Siemens and JAI, would however not fit in the QC station due to dimensional deviation from the existing ones. As precision is critical replacing the cameras would also demand a recalibration of QC station, which would require external and costly expertise. As rebuilding the QC station was not an option in the nearby future and since there where spare parts for the cameras available at GE, the decision to not replace the cameras was taken. However, suggestions on cameras to choose from when the entire station would be rebuilt was looked into in order to ensure compatibility with the other components.
4.1.3 LED
The LED was located inside the QC station and illuminated the part to be examined for one of the cameras. The light for the other camera came from an external light source. The intensity of the LED needed to be controllable through the control unit.

4.1.4 Light source
The external light source (Schott-Fostec) illuminated the part for one of the cameras and the intensity of the light was controlled by an operator through LabVIEW. The light source was connected to the host computer (referred to as “PC” in Appendix D) through a remote RS232 Interface (Schott-Fostec), which handled the communication between the light source and the host computer. The interface was no longer in production, therefore the possibility to replace the external light source and remove the RS232 Interface was investigated. It was found that in a newer version of the same type of light source the RS232 Interface was integrated in the light source unit. Replacing the old light source with this version would have made the control unit less vulnerable, since the RS232 Interface could be removed. By not replacing the old light source the control unit would be dependent on the RS232 Interface and the unit would require reconstruction if the RS232 Interface would break. GE were in the process of replacing all their light sources in the near future so a replacement light source was not of interest at this point. The connections between the light source and the host computer were therefore kept as they were in the previous setup.

4.1.5 Gauge
The gauge was digital and measured the thickness of the inspected part. The measurement signal was transferred to the host computer through USB. The gauge was judged not to be in need of replacing, the connections between the gauge and the host computer were therefore kept as they were in the previous setup.

4.2 Inside the control unit
The control unit was a detached unit that controlled the components of the QC station and supplied them with power. The unit was to control the DC motor and the LED and supply them and the cameras with power. It also needed to control the power supply of the light source.

4.2.1 Programmable logic controller
To control the QC station from LabVIEW, a programmable logic controller (PLC) was needed. The PLC had to be able control the polarity of the motor’s power supply as well as the power supply of the external light source. The existing controller was a 20 Digital I/O controller using the language FST which needed the LabVIEW code to be converted into strings for communication. The language was no longer standard and was troublesome to program as the graphical code had to be transformed into text. As LabVIEW was used as the control environment and there was no in-house programming expertise at the division of GE, the National Instruments controllers and modules was of interest. These could be more easily implemented in LabVIEW than other PLCs due to software compatibility.

4.2.2 Motor control
To be able to control the motor, several methods were investigated. Motor control units such as the NI-9505 module from National Instrument as well as solid state relay modules were looked at to find the most efficient solution for this application.

The NI-9472 digital output module was at first proposed to control the motor. With an external voltage supply range of 0-30 V and power limitations above required ones, the module seemed to be able to control
the motor. Using two outputs connected on either side of the motor the idea was to set one to high and the other on to low in order to drive the motor clockwise. By simply inverting the logical levels of the outputs the motor would rotate counterclockwise. However, the module only had sourcing outputs which meant that when an output was set to low, the potential at that output was not zero or ground but floating. As the output would be left floating no current would be flowing in the motor as there was no closed loop. The NI-9472 would therefore not work for this application.

The motor drive module NI-9505 had a built-in H-bridge for motor control, thus the problem with the floating output could be solved. The module could handle supply voltages in the range of 8-30 V. The number of outputs was limited to two, since these were reserved for the motor this meant that the NI-9505 could not control the power supply for the external light source. The NI-9505 was therefore not an option for the motor control.

The NI-9485 solid state relay module, which had eight outputs that were both sinking and sourcing, could switch the polarity in an H-bridge like way. Using four outputs connected in pairs the motor could be controlled according to the motor control sequence shown in Appendix B. The NI-9485 could handle voltages up to 60 V.

4.2.3 LED driver circuit

The intensity of the LED was determined by the current through it, controlling the current could be achieved through a driver circuit. The current needed for the LED was examined by using a spare QC station together with the previous control unit to not disrupt the production. The LED emitted infrared light but since the cameras were monochrome the color of the light was of less importance. The driver circuit of the previous control unit was supplied with 5 V and the current through and the voltage over the LED was measured with a digital multimeter (DMM). The measured current was 195 mA and the measured voltage was 2.1 V. At first, two solution were produced.

Linear regulator

From the measured data a driver circuit was created. The base of the circuit was the MC78M05CTG, a linear regulator which kept a constant voltage between OUT and GND, Figure 4.3. A resistor and a potentiometer was connected in series between these pins and by varying the resistance of the potentiometer the current to the LED could be controlled. The resistor and potentiometer was chosen so that the current could be varied between 0 to 230 mA according to the measurements and the data sheet of the LED. Because the cameras were driven with a 12 V power supply the number of power supplies could be reduced by choosing the supply voltage of the LED driver circuit to 12 V. A circuit diagram of the solution can be seen in Figure 4.3.

![Figure 4.3: Driver circuit with linear regulator.](image-url)
Buck converter

A buck converter circuit was made using the ZXLD1360 as a switch. The current through the LED was held constant by the $Lx$ pin opening and closing to the $Gnd$ pin when the current measured by $Isense$ deviated from the desired output current. The output current was adjusted by changing the voltage applied to the adjusting pin on the ZXLD1360 between 0.3 V to 2.5 V. By adjusting the voltage the output current would vary between 25% (0.3 V) to 200% (2.5 V) of a chosen nominal output current. To vary the voltage on the adjusting pin a voltage divider with a potentiometer was used.

![Driver circuit with buck converter.](image)

The nominal output current was set according to

$$I_{OUT_{nom}} = \frac{0.1}{R_S},$$

where $R_S$ is the resistor between $V_{in}$ and $I_{sense}$ in Figure 4.4. By choosing $R_S$ to 820 mΩ the nominal output current was set to 122 mA.

Simulation were then made with the potentiometer set to 1.6 kΩ. With this resistance the voltage on the adjusting pin became 1.95 V leading to an output current of 195 mA.

Intermediate events

Feedback regarding the circuits was received from Rejlers and their recommendation was that the LED driver should not be hand soldered. This was to fulfill GE’s demands of easy maintenance components. None of the driver circuits above were therefore of interest for the control unit. On recommendation by Rejlers the possibility of using a ready-made LED driver was examined. However, the LED drivers on the market were made for supplying multiple LEDs with minimum output currents of at least 250-300 mA meaning they were
too powerful for just one LED.

During this period access to the QC station that was in use was possible due to a gap in production. Measurements were made and it was discovered that the LED in that station was different than the one in the spare QC station. This LED emitted white light instead of infrared and the current through it was measured to 20 mA. Heat-shrink tubing had been used on the legs on the LED which meant that the voltage could not be measured. During the measurements it was also discovered that a potentiometer had been placed in series with the LED inside the QC station. This was probably to limit the current from the previous LED driver circuit which had a higher output current than this LED needed.

There were no specifications to be found about this new LED so an investigation was made regarding the possibilities to replace it with an LED with known specifications. A white LED (ESL-R5044TWCE071) with 20 mA rated current, 2.8-3.6 V forward voltage and luminous intensity of 13000 mcd was bought and was placed inside the QC station. With help from the operators the intensity of the LED was adjusted using the potentiometer in the QC station until it was similar to the intensity of the replaced LED. The current through the LED was measured to 3.4 mA and and voltage over it was measured to 2.85 V. According to the data sheet of the LED the current of 3.4 mA corresponded to a luminous intensity of 3000-4000 mcd.

To adapt to the new LED, two new solutions with an output current of 20 mA were produced.

**Pulse-width modulation**

One alternative was to use PWM to control the LED. This could be done with a resistor in series with the LED to limit the current. The output voltage available from the NI-9472, which was the module that we had in mind at the time, was 24 V since that was the voltage level of the DC motor power supply. The maximum switching rate of the NI-9472 was 10 kHz. According to the data sheet of the LED the maximum rating for pulsating current was 100 mA for a pulse lasting 100 µs. The voltage drop over the LED was between 2.8-3.6 V therefore the average voltage of the PWM were chosen to 5 V. To get an average voltage of 5 V from the available 24 V the duty cycle would need to be around 20%. With an average voltage of 5 V assuming a voltage drop over the LED of 3.3 V the series resistor needed to be

\[
\frac{0.2(24 - 3.3)}{20\text{ mA}} \approx 200 \Omega.
\]

The PWM circuit can be seen in Figure 4.5.

![PWM circuit](image-url)
This setup was simulated in LTspice using a 24 V voltage source which was pulsed with a frequency of 2 kHz and a duty cycle of 20%.

Current limiter

The second alternative was to add another power supply of 5 V in the control unit and use a current limiter. The LED were to be connected in series together with a potentiometer and a resistance. The maximum continuous current the LED could handle was 30 mA meaning that the resistance of the resistor needed to be at least

$$\frac{5 - 3.3 \text{ V}}{30 \text{ mA}} \approx 57 \Omega$$

to limit the current. To achieve 20 mA the potentiometer needed to be set to

$$\frac{5 - 3.3 \text{ V}}{20 \text{ mA}} - 57 \Omega \approx 28 \Omega$$

The current limiter circuit can be seen in Figure 4.6.

4.3 Thermal issues

Since the life expectancy of the components could be halved for every 7 °C increase in temperature it was of most importance to keep the temperature around the components low. Of all used components the power supplies were the most sensitive to heat. According to the data sheet the power that could be drawn from the power supplies would decrease if the temperature would rise above 40 °C and if the temperature would rise above 60 °C the power supplies could be damaged. To meet the temperature demands and to make sure that power losses would not be a problem, the total power was estimated. Power losses for the power supplies were calculated using the input power multiplied with $1 - \eta$, where $\eta$ was the efficiency. For the PLC the power losses were estimated from information found in the data sheet. The efficiency of the cameras and the RS232 Interface were approximated to 70%. Wires and connectors were considered loss-free. The individual power losses were added together to get a total power loss.

To estimate the heat build-up inside the control unit the total power loss was used as the dissipated power. The thermal dissipation inside the enclosure was assumed to have reached steady state where the air temperature inside the control unit was equal to the air temperature around the component. The convection
between the component and the surrounding air inside the control unit could therefore be ignored. The metal enclosure of the control unit was assumed to be sealed. The ambient temperature in the room was assumed to be 20 °C. By using the heat transfer coefficient interval for free convection of gases (2-25 Wm$^{-2}$K$^{-1}$) the corresponding temperature on the surface of the box was calculated using Equation 2.1. The calculated surface temperature was then used in Equation 2.2 to calculate the temperature inside the box. Here the thermal conductivity of the metal enclosure was approximated to 45 Wm$^{-1}$K$^{-1}$ which was the thermal conductivity for steel [17]. The unobstructed surface area and material thickness used in the equations were set according to a reference metal enclosure with measurements 250x200x150 mm and with a wall thickness of 1.5 mm. Since the heat transfer coefficient was unknown the calculated temperature inside the box was plotted against the interval.
Chapter 5

Results

5.1 Flyback voltage

The measurements of the flyback voltage from the DC motor windings can be seen in Figure 5.1, the negative supply voltage is due to the polarity of the probes. The graph shows three measurements, one with 24 V supply voltage (blue), one with 20 V supply voltage (red) and one with 20 V supply voltage and a varistor in parallel with the motor (yellow).

![Figure 5.1: Measured flyback voltages.](image)

As shown in Figure 5.1 when lowering the supply voltage from 24 V to 20 V the flyback still occurred. The magnitude was lower, yet pronounced. The impact of the varistor greatly suppressed the voltage from 56 V to 36 V but also prolonged the discharge time of the coil.

The simulation of the Zener diode setup shows the dampening characteristics of the circuit, see Figure 5.2.
Since the number of components were to be held at a minimum the varistor solution was chosen.

### 5.2 Programmable logic controller and motor control

The PLC that was chosen was the 8 channel NI-9485. Due to its relay features its outputs could be either sinking or sourcing, meaning that it could be driven as an H-bridge through LabVIEW. This was a requirement for the module in order to control the bipolar motor without adding external components and with its number of channels it could also control the external relay. The module was also capable of handling the flyback voltage with its voltage rating of 60 V. The single slot cDAQ-9171 was chosen as chassis for the module. A single slot was judged to be enough for this application. This chassis was preferred due to its USB connection with the host computer which meant that it could receive its power through USB.

The PLC was controlled as an H-bridge through LabVIEW according to the motor control sequence shown in Appendix B. Delays of 0.2 s where added between the signals to make sure that the module was not short circuited and the length of the delays were set to also give the motor enough time to discharge its coils.

### 5.3 Cameras

The suggestion of cameras that was presented were the Basler Ace area scan cameras which were a series of compact cameras. The Ace cameras came in various performances, with resolutions up to 14 megapixel and frame rates up to 751 frames per second. The series implemented one of two different camera sensor techniques, it used either a CCD sensor or a complementary metal oxide semiconductor (CMOS) sensor. For this application either of them would work since they both would improve the image compared to the previous cameras. Regarding the resolution and frame rate, as the object examined in the QC station was still, the cameras with high resolution would be preferred over the ones with a high frame rate. The Ace cameras had a housing size of approximately 40x30x30 mm, significantly larger compared to the previous cylindrical shaped cameras which had a length of 50 mm and a diameter of 12 mm. The Ace series came in GigE Vision, USB3 Vision or Camera Link versions meaning that they could easily be implemented with National Instrument’s product range. The cameras were directly compatible with the LabVIEW image acquisition, making the programming easy to implement as a range of existing virtual instruments were available. The Ace cameras used the universal C mount for external lenses which meant that there would be a wide range of lens options.
5.4 LED driver circuit

The linear regulator and the buck converter circuits were built for another LED than the one in the QC station in use. However, the same ideas could have been applied for the 20 mA output current which the other LED demanded. In such cases the voltage of the power supply would have been lowered from 12 V to 5 V.

5.4.1 Linear regulator

The power lost in the potentiometer and resistor was compared with usable power of the LED. To reach an output current of 195 mA the potentiometer was set to give a resistance of 3.6 $\Omega$ achieve a total resistance of 25.6 $\Omega$ with the resistor. Since the voltage over the resistor and potentiometer was 5 V the power losses in these components was 0.97 W, according to Equation 2.4. Assuming a voltage drop over the LED of 2.1 V the power of the LED was 0.41 W, according to Equation 2.3. As the current decreases (resistance increases) the power lost in the resistor and potentiometer is reduced but the power losses in the resistor and potentiometer is always higher than the useful power, see Figure 5.3. There are also losses in the linear regulator itself which are not taken into account here.

![Figure 5.3: Calculated useful power (red) and power losses (blue) for the linear regulator circuit.](image)

5.4.2 Buck converter

The simulation of the buck converter circuit showed that the current through the branch with the voltage divider was 1.23 mA. A total resistance in the branch of 9.8 k$\Omega$ meant that the power loss in the branch was 14.8 mW, according to Equation 2.4. At the same time the power to the LED (depicted in Figure 4.4 using LXHL-BW02) was 0.41 W, according to Equation 2.3, using that the current through the LED was 195 mA and the voltage over the LED was 2.1 V. This distribution was expected since the current through the voltage divider is negligible in comparison to the current through the LED due to the low resistance in the branch with the LED. There are also losses in the ZXLD1360 itself which are not taken into account here.
5.4.3 Pulse-width modulation

In the simulation of the PWM solution the average voltage of the supply was 5.3 V, the average voltage drop over the LED was 0.9 V and the average current through the LED was 21.7 mA. The instant current through the LED together with the instant voltage supplied and the instant voltage over the LED can be seen in Figure 5.4.

![Figure 5.4: Simulation of PWM circuit.](image)

5.4.4 Choice of driver circuit

Since the LED driver circuit was supposed to be easy to replace the linear regulator circuit and the buck converter circuit were not of interest as they would require soldering. As previously stated an LED driver would not fit this application either.

The efficiency of the PWM solution was low since the behavior of the LED is not linear (the voltage drop over an LED is almost constant regardless of the voltage supplied). Using a PWM voltage of 24 V meant that the majority of the voltage during on-time would be dropped over the resistor causing most of the energy to be dissipated as heat. If the PWM voltage had been closer to 5 V the efficiency would have been higher since the resistance would have needed to be lower to achieve a current of 20 mA. A lower duty cycle than 20% at 24 V could also have made the solution more efficient. Lowering the duty cycle would reduce the average current meaning that the resistance again could have been lowered. However, simulations showed that a lower duty cycle than 20% together with a resistance lower than 200 Ω would have lead to current peaks over 100 mA which could have damaged the LED. The PWM solution was therefore not applicable.

This left the current limiter as the simplest and most durable solution between the ones that were investigated. With only the need of soldering a current limiting resistor to one of its legs it was easy to build and because the amount of components is limited to two it was also cheap to buy. However, it was far from the most efficient due to power losses, but because easy maintenance was prioritized over efficiency the current limiter was the best solution for the control unit.

From the measurements made with the LED that was bought it could be concluded that the previous LED could be replaced with an LED rated at 20 mA current, 2.8-3.6 V forward voltage and luminous intensity of 5000 mcd. This LED is common and could be easily found at an electronic dealer. The 5034W2C-DSE-C from HuYuan would be a candidate.
5.5 Power supplies

For the power supplies the Omron S8VK-G model was chosen. They were preferred since they were DIN mounted, had 10 years of life expectancy and had a compact design. All three types of power supplies were available in the S8VK-G series. In the new design the 5 V and 12 V power supplies were moved inside the control unit, having previously been external.

5.6 Relay

The relay was chosen to be the J73KN-A-40 24D, a four-pole, normally open, DIN mounted relay. It had a coil voltage of 24 V which meant that it could be opened by a signal from the PLC. By using four poles all the power supplies could be connected to the relay which meant that the entire QC station could be turned on and off using just one signal. The relay was a voltage regulated relay which meant that it would not draw a high amount of power through the signal sent from the PLC.

5.7 Metal enclosure

For the metal enclosure a two-piece enclosure with an aluminum front plate and ventilated steel top and bottom plates was chosen. It was of importance that the top of the enclosure could be removed for easy maintenance, which was why this enclosure was chosen. The enclosure measured 250x200x150 mm, the thickness of the front and rear plates were 1.0 mm and the thickness of the top and bottom plates were 1.5 mm.

5.8 Thermal issues

The calculated power losses for the individual components can be found in Table 5.1. As can be seen, the total estimated power loss inside the control unit was approximately 4.9 W.

Table 5.1: Power losses.

<table>
<thead>
<tr>
<th>Component</th>
<th>Power loss [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLC</td>
<td>1.5</td>
</tr>
<tr>
<td>Power supply 5 V</td>
<td>0.01</td>
</tr>
<tr>
<td>Power supply 12 V</td>
<td>0.74</td>
</tr>
<tr>
<td>Power supply 24 V</td>
<td>0.022</td>
</tr>
<tr>
<td>RS232 Interface</td>
<td>0.36</td>
</tr>
<tr>
<td>Cameras</td>
<td>2.22</td>
</tr>
<tr>
<td>Total</td>
<td>4.9</td>
</tr>
</tbody>
</table>

The plotted temperature inside the control unit can be seen in Figure 5.5. As previously stated the dissipated power used in the calculations was the total power loss, 4.9 W from Table 5.1. The interval for the heat transfer coefficient used was 2-25 Wm$^{-2}$K$^{-1}$. 
From the assumptions made it can be seen in Figure 5.5 that the temperature will never rise above 33.3 °C which will not damage the component, but might shorten the life span. In order to keep the temperature at a lower level a fan was placed on the rear end of the control unit to create a higher pressure inside the unit forcing the hot air out of the unit.

5.9 Durability

Cartridge fuses were added to protect the DC motor, the LED, the cameras and the fan as well as their cables and connectors. The four fuses were placed inside four DIN mounted terminal blocks. Five DIN mounted terminal blocks were added to make multiple connection to the same node as well as merge wires with different cross sectional areas. For terminals with more than one wire connected, ferrules were used in order to make a strong and durable connection.

5.10 Connections and placements

For the circuit diagram of the control unit see Appendix C. For connections between the control unit, the host computer and the QC station see Appendix D.

The final set of components was placed in the enclosure according to Figure 5.6. To secure the components inside the box two DIN rails were mounted on the bottom plate of the control unit. DIN rail mounted components were chosen to the extent possible. The relay, the power supplies and the terminal blocks were all chosen to be DIN rail mounted. The power supplies were mounted together on a separate DIN rail. This was to meet the spacing recommendation from the manufacturers of a minimum spacing of 20 mm creating an adequate airflow. Under the assumption that the power supplies would dissipate heat they were placed close to the air ventilation in the lid of the enclosure. That enabled the hot air to dissipate through the lid and reduce the negative effect of heat on other components. On the other DIN rail the relay and the terminal blocks were mounted. The cDAQ-9171 was mounted along the inside plate of the control unit by a cable tie that was attached through a cable tie mount on the bottom plate. In the same way the RS232 Interface was mounted along the opposite side plate. The camera control units were mounted on the inside
of the top plate. This was to be able to let the cables for the cameras run through the back plate of the unit so that the lid could be taken off without unplugging the cameras. To reduce the risk of interference with control signals, the terminals were placed as close to the wall connectors of the enclosure to minimize the cable lengths. All contacts were placed on one side of the enclosure to hide cables from the operator and reducing risk of disruptions of the cables.

![Diagram of component placement](image)

Figure 5.6: Placement of the components inside the control unit.

The placement of the contacts can be seen in Figure 5.7. On the top of the rear plate a hole was cut out for the cables from the camera control units. The sharp edge of the hole was covered by a piece of plastic to protect the cables. The fan was placed so that the cool air would reach the power supplies.
Figure 5.7: Placement of contacts and fan on the rear of the control unit.
Chapter 6

Discussion

6.1 Flyback voltage

In the tests with the varistor the change of supplied voltage from 24 V to 20 V did not affect the flyback voltage peak significantly, see Figure 5.1. The same behavior could therefore be expected with a supply voltage of 24 V with only a slight rise in the flyback voltage. From the test with the varistor and the Zener diodes simulation, it can be concluded that the flyback voltage can be suppressed with either solution. That the choice fell on the varistor solution was because it only needed one component and because the NI-9485 could handle voltages up to 60 V. If that voltage would have been lower it could have been better to use the Zener diodes. With them, a specific voltage level, which the flyback voltage would not exceed, could have been set through the choice of the Zener diodes’ reverse voltage.

6.2 Programmable logic controller and motor control

The optimal PLC for the application would have been a PLC specifically made for motor control, such as a DC brushed servo with additional digital outputs. This would have eliminated the need of programming an H-bridge with delays, which would have lead to a more foolproof solution. No module with the desired properties was available in National Instruments’ assortment, but since one of the priorities was to ease the programming and since LabVIEW was the software in use, National Instruments’ products were preferred. Among the modules the best option was the NI-9485 combined with the cDAQ-9171 with respect to price, durability and the demanded system requirements. There might have been other PLCs from other manufacturers that had the desired properties and this was something that could have been examined in more detail.

6.3 LED driver circuit

The PWM solution probably would have been the best for the LED driver circuit if the voltage level from the PLC would have been 5 V. This would have been a more natural use of the PWM, 100% duty cycle would then correspond to full intensity from the LED. For the PWM solution to work another module than the NI-9485 would have been needed. The outputs of the NI-9485 could not be switched fast enough for the PWM to work, at 90% duty cycle it had a switching rate of one operation per second. With such a low switching rate the LED would have flickered.

If the demands on easy maintenance would have been lower and assuming that the NI-9485 had been chosen as the PLC, the buck converter circuit probably would have been the best choice for the LED driver circuit. The buck converter circuit had a higher efficiency than the linear regulator circuit and even if it required soldering it would not have been that much work to solder a couple of back-up circuits in case the original one would fail.
6.4 Thermal issues

The estimations of the heat build-up inside the control unit could have been further investigated. The calculations were made as simple as possible due to lack of knowledge and the limited time. Because the limited knowledge in the field of thermodynamics a good approximation of the heat transfer coefficient was hard to make. Approximating the wrong heat transfer coefficient, which could range from 2 to 1000 depending on the situation, could affect the result significantly. With further knowledge a better approximation of the heat transfer coefficient could have been made, giving a more precise estimation. If more time had been available, more advanced assumptions using forced convection instead of just free convection could have been made. By for example taking the ventilation of the room into account. This would have affected the heat transfer coefficient. With more time available the heat build-up could have been simulated in for example SolidWorks. A closer investigation might have lead to a solution where a fan was considered unnecessary. For this project however, it was decided that it was better to not take any risks.

6.5 Future proofing

One of the goals of the project was to future proof the electronic control unit. This was attempted to be made through the use of stock components that were both durable and easy to replace. Safety measures were taken by adding cartridge fuses. However, the future proofing was partially held back by the components of the QC station. As mentioned earlier, GE were in the process of replacing all their light sources. The external light source for the QC station was therefore kept as it was, meaning that the RS232 Interface would still be part of the control unit. Since the interface no longer was in production it would have been better to replace the light source so that the test station would not be dependent on an irreplaceable component.

Another irreplaceable component was the cameras, which were also kept as they were. However, it was not easy to find a good replacement for the cameras due to the design of the QC station. Cameras in the same size as the previous ones were rare, which would mean that the QC station would need to be rebuilt if the cameras were to be replaced, this was not an option. Since there were spare parts for the cameras available at GE, they were therefore not as vulnerable as the RS232 Interface.

In order to fully future proof the test station, GE was recommended to rebuild the entire station. The rebuild would include replacing the cameras for digital ones with higher resolution, replace both the LED and external light source with digitally controlled lights and even consider implementing digital image recognition in order to recognize unwanted particles from the object and automate the control process. Rebuilding the entire test station would remove all the vulnerable components eliminating the risk of components breaking due to age. Replacing these components would reduce the unnecessary conversions in the connections between the control unit and QC station, see Appendix C.
Chapter 7

Conclusion

The electronic control unit was future-proofed using stock components as far as possible, and using components that were durable and easy to replace. The future proofing was however limited since the QC station still contained components that would be hard to replace. If the project would have included replacing the QC station as well as the control unit the entire test station could have been future-proofed. The control unit was improved by using a PLC that was directly compatible with LabVIEW. It was also improved by connecting all of the power supplies to the relay which meant that the entire QC station would be turned off when the operator quit the LabVIEW interface. The 5 V and 12 V power supplies, which were external in the previous control unit, were placed inside the control unit to limit the amount of cables outside the unit and create a clean look. The Basler Ace cameras were presented to GE as an option for a future developed station with higher resolution and better compatibility. Another improvement was the addition of cartridge fuses to protect the components. A detailed technical documentation was created where the functions and the connections of the control unit could be understood and where a complete component list could be found. The functions were described through a specification of requirements while the connections were described using a circuit diagram and block diagrams over the connections. Through this technical documentation maintenance will cost less and be less troublesome. Through this project GE has received a new, future-proofed, electronic control unit together with a full technical documentation of it as they requested.
Chapter 8

References


Appendix A

Specification of requirements

The electronic control unit is to supply the:

- Schott-Fostec light source, 150 W halogen lamp which runs on 230 VAC.
- Programmable logic controller (PLC).
- CV-M532 Remote Head Monochrome CCD Camera, runs on 12 VDC which needs to be supplied to two camera control units. The cameras consumes 3.7 W each.
- Light-emitting diode (LED) inside the QC station.

The electronic control unit is to control the:

- Bipolar DC Motor. Runs on 24 VDC. The maximum current drawn by the motor is 250 mA and it has a nominal power of 0.22 W.
- Voltage supply for the Schott-Fostec light source.
- Luminous intensity of the LED in the QC station.
Appendix B

Motor control sequence

Figure B.1: Motor control sequence.
Appendix C

Circuit diagram of control unit

Figure C.1: Circuit diagram of the electronic control unit.
Appendix D

Connections

Connections within the control unit

The electronic control unit is connected to the wall socket through a power cord. The NI-9485 receives its control signal from the power supply which converts 230 VAC to 24 VDC (1, figure D.1). The electronic control unit controls the motor with a digital signal of 24 VDC from the NI-9485 module (7, figure D.1). Through the relay the unit also controls the 5 VDC power supply of the LED in the QC station and the fan on the rear end of the unit itself (2, figure D.1), the 12 VDC power supply of the camera control unit in the control unit (3, figure D.1) and the 230 VAC power supply of the Schott-Fostec light source (4, figure D.1).

![Block diagram for the connections within the electronic control unit.](image)

Connections with the QC station

The NI-9485 sits in the cDAQ-9171 which is connected to the PC through USB. The cable is fed through a hole in the rear plate of the electronic control unit. The connection between the NI-9485 and the QC station is made through a wall mounted D-sub (DE9) contact on the control unit. A D-sub (DE9) cable then connects the LED and motor through a screw terminal in the QC station (2, figure D.2).

The cameras and the camera control unit are the same that was used in the previous electronic control unit. The camera control units are mounted on the inside of the lid of the electronic control unit. The cameras are connected to the camera control unit which is in turn connected to the IMAQ PCI-1409 which sits in the PC (1 and 3, figure D.2). The cables from the camera control units are fed through the same hole in the back plate of electronic control unit as the cable connecting the cDAQ-9171 and the PC. One of the
cameras are connected directly using a coaxial cable while the other camera uses a coaxial to D-sub (DB-25) converter and this D-sub (DB-25) is then connected to the IMAQ PCI-1409.

The Schott-Fostec RS232 Interface is also a reused component from the previous control unit. It is connected to the PC through a D-sub (DB-25) to D-sub (DE9) converter and a D-sub (DE9) to USB converter (7, figure D.2). The USB is then connected to the PC. On the other end, the interface is connected to the Schott-Fostec light source through D-sub (DE9) (5, figure D.2). In this D-sub (DE9) connection the Interface also receives its 12 VDC voltage which is supplied by the Schott-Fostec light source.

The gauge which measures the thickness of the part is connected to the PC through a Digimatic to USB converter (6, figure D.2). The gauge is also a reused component from the previous control unit.

Figure D.2: Block diagram for the connections between the electronic control unit, PC and QC station.
# Appendix E
## Component list

Table E.1: Component list.

<table>
<thead>
<tr>
<th>Art.nr.</th>
<th>Component</th>
<th>Type</th>
<th>Qty</th>
<th>Price (SEK)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>781425-01</td>
<td>cDAQ chassis</td>
<td>NI-9171</td>
<td>1</td>
<td>3,105.00</td>
<td>NI</td>
</tr>
<tr>
<td>779600-01</td>
<td>Module</td>
<td>NI-9485</td>
<td>1</td>
<td>3,620.00</td>
<td></td>
</tr>
<tr>
<td>520497</td>
<td>Metal enclosure, 250x200x150 mm</td>
<td>GSS10</td>
<td>1</td>
<td>268.22</td>
<td>Conrad</td>
</tr>
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<td>136-24-087</td>
<td>Relay</td>
<td>J7KNA-AR-40 24D</td>
<td>1</td>
<td>313.00</td>
<td>ELFA</td>
</tr>
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<td>110-41-387</td>
<td>Power supply 24 VDC</td>
<td>S8VK-G01524</td>
<td>1</td>
<td>257.00</td>
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<td>110-41-386</td>
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<td>S8VK-G01512</td>
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<td>257.00</td>
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<td>1</td>
<td>257.00</td>
<td></td>
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<td>143-22-327</td>
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<td>1</td>
<td>34.40</td>
<td></td>
</tr>
<tr>
<td>143-21-196</td>
<td>Power socket</td>
<td>PX0675/63</td>
<td>1</td>
<td>22.10</td>
<td></td>
</tr>
<tr>
<td>148-20-720</td>
<td>Blade receptacle, extra rails</td>
<td>9-160463-2</td>
<td>3</td>
<td>7.51</td>
<td></td>
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<tr>
<td>148-20-709</td>
<td>Blade receptacle</td>
<td>9-160313-2</td>
<td>4</td>
<td>4.15</td>
<td></td>
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<tr>
<td>300-75-354</td>
<td>Cable tie</td>
<td>RND 475-00446</td>
<td>1</td>
<td>37.00</td>
<td></td>
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<td>300-09-418</td>
<td>Strd. wire R 0.75 mm² AWG 18-19</td>
<td>Helukabel 23402</td>
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<tr>
<td>300-09-633</td>
<td>Strd. wire B 0.75 mm² AWG 18-19</td>
<td>Helukabel 52881</td>
<td>5</td>
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<tr>
<td>155-40-224</td>
<td>Strd. wire R 0.75 mm² AWG 18-19</td>
<td>RADOX 125 0.75 MM2 RED</td>
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<tr>
<td>155-40-208</td>
<td>Strd. wire B 0.75 mm² AWG 18-19</td>
<td>RADOX 125 0.75 MM2 BLACK</td>
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<td>8.76</td>
<td></td>
</tr>
<tr>
<td>300-21-352</td>
<td>Strd. wire G/Y 2.5mm² 13 AWG</td>
<td>H07V2-K 2.5 MM²</td>
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<td>12.40</td>
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<td>155-26-124</td>
<td>Strd. wire R 2.08 mm² 14 AWG</td>
<td>3079 RD001</td>
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<td>9.78</td>
<td></td>
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<tr>
<td>155-46-247</td>
<td>Strd. wire B 2.08 mm² 14 AWG</td>
<td>7046 BK001</td>
<td>5</td>
<td>21.00</td>
<td></td>
</tr>
<tr>
<td>155-06-123</td>
<td>Heat-shrink tubing</td>
<td>W-1-H-6.0MM-BLACK</td>
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