Development of a Multi-Level Emergency Stop System for Unmanned Vehicles

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Abstract

As the use of unmanned vehicles continues to grow, so does the need for systems to safely test and operate these vehicles. While there are safety systems designed for this purpose, they are often developed for a specific vehicle platform. The Multi-Level Emergency Stop (MLES) system provides three user-defined emergency response contingencies that can be adapted to a wide variety of unmanned vehicles.

The Multi-Level Emergency Stop system is designed to be an ad-on safety system that can be integrated into ground, air, or surface unmanned vehicles. A complete MLES system consists of a hand held transmitter and a vehicle mounted receiver. The three levels of contingencies are controlled by three switches on the transmitter. These switches engage and disengage contacts located in the receiver via a wireless link. The function of these contacts is determined by the user for each unique application.

Presented in this thesis is the detailed hardware design and software layout of the Multi-Level Emergency Stop system. Also included are the performance results and operational tests.

Acknowledgments

I would like to thank the many people that have contributed to this thesis and my graduate studies. Without the love and encouragement of my parents, Bob and Karen Avitabile, none of this would have been possible. Their support has provided me with incredible opportunities for which I am forever grateful.

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I would also like to thank all my fellow researchers a Virginia Tech. I am lucky to have had the experience of working with such talented and motivated individuals. Spanning the course of several years, there have been many people that have contributed to the development of the Multi-Level Emergency Stop system.

This project was initially a joint effort with Ben Hastings. Ben was responsible for the initial hardware design, and has helped advance the development of the project throughout. The evolution of the enclosures was the work of Sean Baity. His designs have transformed this project into a finished product. I would also like to thank Dave Anderson and Shane Barnett for their assistance with the final enclosure design and Cheryl Bauman for her help with the final testing. It was also important that the connectors used on the Multi-Level Emergency Stop satisfied the strict requirements of Brett Gombar.

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Chapter 1

Introduction

The use of unmanned vehicles in today's society is rapidly expanding. Unmanned ground, air, and surface vehicles are quickly becoming commonplace in a wide variety of applications, especially military. These complex unmanned systems contain sophisticated controls and navigation algorithms. This level of complexity requires enforcement of strict safety measures during their testing and operation. The most effective safety measures involve the use of independent safety systems that can be integrated with an existing vehicles hardware and software systems.

The Multi-Level Emergency Stop (MLES) system is designed to provide an independent wireless safety link for a wide variety of unmanned vehicles. The versatile design of the MLES allows for integration in unmanned ground, air and surface vehicles by providing three levels of contingencies in a tightly integrated package tailored for use with unmanned systems.

A wireless emergency stop utilized in unmanned systems provides the ability to safely disable a vehicle remotely. Safely disabling an unmanned vehicle requires a unique implementation specific to the particular platform of the vehicle. For example, a ground vehicle could be safely immobilized by disabling the vehicle's power plant. An identical implementation in a rotary winged unmanned aerial vehicle during flight would have an adverse effect resulting in an uncontrolled descent. For successful implementation of an emergency stop system on an unmanned aerial vehicle, a higher number of contingencies are needed compared to that of a ground vehicle.

Failure of a navigation sensor of an unmanned aerial vehicle during flight is a failure mode that presumably requires the actuation of an emergency stop. Unlike a ground vehicle, cutting power to the system could result in an unsafe state, sending the vehicle crashing to the ground. One possible resolution to this problem would be the implementation of a mult-level emergency stop. Rather than a single level that would cut power, several less severe levels could be implemented. These levels would provide a method for bringing a vehicle safely to the ground.

Specifically, three levels of contingencies would enable an aerial vehicle to descend safely. The least severe of the three levels can be configured to place the aerial vehicle in a hover where its current position is maintained. This provides time to properly assess the problem and plan future actions. If the problem persists, the next level of contingency can be implemented as a controlled descent.

This allows for the aerial vehicle to be safely transported to the ground. Once on the ground, the final and most severe level can cut vehicle power if needed.

Considering the requirements needed for safely disabling an aerial vehicle, the Multi-Level Emergency Stop system incorporates three levels of contingencies. This allows the MLES to be incorporated into a wide variety of vehicle platforms that require up to three levels of emergency stop contingencies.

The Multi-Level Emergency Stop system consists of two major components, a transmitter and a receiver. Each of the three levels of the Multi-Level Emergency Stop system is actuated by switches on the transmitter. These switches engage or disengage corresponding outputs on the receiver.

1.1 Motivation

In June of 2004, Virginia Tech was granted a contract by RDECOM, the Army's Research, Development & Engineering Command to develop the JOint Unmanned Systems Test, Experimentation & Research (JOUSTER) facility. The primary focus of JOUSTER is the evaluation and testing of unmanned vehicle systems. The JOUSTER facility provides the infrastructure and instrumentation to support a wide range of vehicle platforms.

Since its inception, the goals of JOUSTER have been to develop and support the testing of both aerial and ground unmanned vehicle platforms. For this reason, one of the goals of JOUSTER was to develop a generic safety system that could be adapted for use on a variety of vehicle platforms.

The primary design goal of the Multi-Level Emergency Stop, as the name implies, is the multi-level functionality. The specific implementation of the levels is unique for each application and specific to the vehicle platform. For example one particular implementation of an unmanned aerial vehicle could be implemented in the following manner. Level-I would allow for the aerial vehicle to halt movement and maintain a steady hover. Level-II could then be implemented to allow the vehicle to slowly enter a controlled descent. Finally Level-III would then cut all power to the vehicle one the vehicle is safely on the ground.

Unlike an aerial vehicle, a ground vehicle implementation would not require the use of three levels of emergency stop. Implementation of an emergency stop system in a ground vehicle could potentially be done with the use of two levels. The first, less severe level, could bring the ground vehicle to a controlled stop. Once stopped, power to the vehicle could be cut through the use of a second level, to ensure no further movement. Accommodating both ground and aerial vehicles in the above scenarios required the design of the MLES to incorporate at least three levels of contingencies, although not all three levels would need to be implemented in every situation.

The function of the Multi-Level Emergency Stop system is to provide a remote interface to an unmanned vehicle. Implementation of the levels is unique to each vehicle platform. The vehicle interface of the MLES needed to support a wide range of vehicle specific hardware. For this reason, the vehicle mounted receiver needed to provide a variety of interfaces methods that would update the unmanned system of the status of the Multi-Level Emergency Stop. These include high current contacts, digital outputs, and serial communications. The high current outputs of the MLES could be directly coupled to a vehicle's existing electronics, and used for cutting power to actuators or relays on the vehicle. The digital outputs and serial interface would allow for the state of the MLES system to be known by the software running on the vehicle.

In addition to the multiple levels, the MLES needed to operate at a range that would not restrict the effective operating range of the unmanned vehicle. It was important that the wireless link on the MLES could operate at a line of site distance of at least one mile. With the prevalence of 802.11 networks on the vehicles, the operating frequency of the system would have to be different than the 2.4GHz or 5Ghz bands that were occupied by the this existing infrastructure.

Runtime of the MLES was also a contributing design factor. The MLES needed a runtime of 8 hours to support a full day of vehicle testing. These requirements were to fit in a compact portable package that could be used in a multitude of unmanned systems.

1.2 Existing Safety Systems

The design of the Multi-Level Emergency Stop system began by evaluating existing radio systems. Several commercially available radio systems were evaluated and used to refine the design goals of the MLES.

The concept of a remote emergency stop system is not new. Remote safety systems have been in use for many years in a broad range of applications. A common application for wireless safety systems is in industrial automation. Several of these systems, were evaluated during the conceptual development of the Multi-Level Emergency Stop system.

The FRF-0302U Remote Control System from LOR Manufacturing (Figure 1.1) is designed primarily for use in industrial control applications such as boom cranes, lifts, concrete boom pumps and conveyors. This system offers three channels that remotely operate 3 SPST (single pole single throw) relays. The system has an operating range of 65 feet, and has a continuous transmission battery life of over 60 hours. The entire system is housed in a small lightweight package conducive to handheld operations [14].

Figure 1.1: Futaba FRF-0302U 3-Channel R/C System [14]

Other alternatives considered were those specifically designed for use with unmanned vehicles. The unmanned systems industry is relatively small compared to the vast number of applications that fall within the scope of industrial control. As a result, safety systems specifically designed for unmanned vehicles are limited.

Another alternative is shown in Figure 1.2. This ORI-SR safety system from Omnitech Robotics is designed for unmanned ground vehicle use. This system offers two levels of functionality, one for immobilizing a vehicle and the other for temporarily pausing. Designed for use with unmanned vehicles, the ORI-SR is also equipped with digital outputs on the receiver. These outputs integrate into a vehicle's data acquisition system to inform the vehicle of its current state. This digital output functionality easily allows a vehicle to read the status of the pause level in software, placing the vehicle in a software controlled stopped state.

The Omnitech Robotics Safety Radio System provides a maximum line of sight range of 90 miles. This system also incorporates a GPS vehicle tracking system and data logging capabilities. Both the receiver and transmitter measure 10.125 x 6.25 x 3.5 inches at a weight of 10 pounds. The transmitter and receiver also require an external 12V power source. The features of this radio system come with a significant price tag of $12,000 [15].

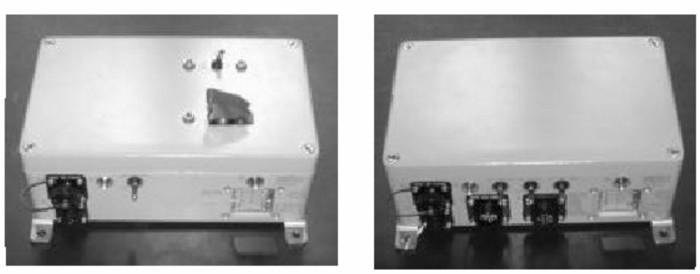

Figure 1.2: Omnitech ORI-SR safety radio system [15]

Detailed specifications of the above systems can be seen in Table 1.1 along with the design goals of the Mult-Level Emergency Stop. While these products offer superior performance in their intended applications, there are several shortcomings of these systems that limit them from being implemented as a general purpose unmanned vehicle emergency stop system.

Table 1.1: Comparison of Existing Radio Systems and MLES Design Specifications

	FRF-0302U	**ORI-SR**	**MLES**
Frequency	304MHz	902-928MHz	900MHz
Levels	3	2	3
Range	65 ft	90 mi	1 mi
Battery Life	60 hrs	N/A	8 hrs
Tx Size	5.71 x 1.5 x .75	10.13 x 6.25 x 3.5	Handheld
Rx Size	5.59 x 4.53 . 1.93	10.13 x 6.25 x 3.5	Handheld
Tx Weight	2.5 oz	10 lbs	< 3 lbs
Rx Weight	14.1 oz	10 lbs	< 3 lbs
Contact Type	SPST	SPST	SPDT
Digital Outputs	NO	YES	YES
Serial Interface	NO	NO	YES
Response Time	150 ms	< 100 ms	< 100 ms
User Configurable	NO	NO	YES
Analog Channels	0	0	2
Cost	$1,000.00	$12,000.00	< $1,000

The primary requirement of the Multi-Level Emergency Stop system is the ability to provide three levels of contingencies. While there are systems that offer three levels, such as the FRF-0302U, they are not tailored for use with unmanned vehicles, and do not provide a digital interface. The LOR Manufacturing radio system has sufficient battery life and a compact transmitter package that meets the criteria of the MLES design goals, however the range is a severely limiting factor.

One of the major downfalls of the FRF system is the range. With a maximum distance of 65ft, the capability of many unmanned vehicles would be severely limited.

The Omnitech Safety Radio System offers many desirable features. With a line of sight range of 90 miles, and a digital interface, the Omnitech radios are well suited for many ground vehicle platforms. The size and weight of the ORI-SR limits its use to large vehicles. For many mid-sized unmanned platforms 10lbs is a significant percentage of their payload capacity.

As listed in Table 1.1 there are several other design specifications incorporated into the Multi-Level Emergency Stop system. One of these features involved the addition of two analog channels. These analog outputs on the receiver would correspond to the position of a two axis joystick located on the transmitter. These analog outputs could then be used to remotely operate the vehicle through the emergency stop system.

Other design specification included the use of single pole double throw (SPDT) relay outputs. This would allow for greater versatility of the relay outputs. The response time of the system also needed to be comparable to existing systems. An update frequency of 10Hz was decided upon, therefore limiting the maximum response time to less than 100ms.

One of the key design features of the MLES system was the high level of customization. In an effort to adapt to multiple vehicle platforms, many operational settings of the MLES system are user configurable. In order to accomplish this, a serial interface was needed on both the transmitter and receiver. The purpose of the serial interface on the receiver was twofold. In addition to serving as the configuration interface, it also would serve as a communications link to the unmanned vehicle. The serial interface allows integration into vehicles that do not have a data acquisition system to read the digital inputs. The status of the MLES system can be read over RS-232 communications.

One of the driving features for developing the Multi-Level Emergency System was to develop a system at a fraction of the price of comparable systems. As seen in Table 1.1, the price of a comparable OR-SRS system is $12000. A final parts and labor cost of $1000 per unit was set for the MLES system.

1.3 Disclaimer

Users of the Multi-Level Emergency Stop system are responsible and must always assume responsibility for safe operation. It is up to the users to implement a comprehensive safety program to ensure safe vehicle operation.

Chapter 2

Transmitter Hardware Design

2.1 Overview

The Multi-Level Emergency Stop system consists of two primary components that form a wireless link between the unmanned vehicle and an operator. The operator side of the MLES system is the transmitter. The transmitter wirelessly transmits the status of the system to the vehicle side, or the receiver. Once the data from the transmitter arrives at the receiver, the data it is interpreted and the corresponding actions are taken.

The Multi-Level Emergency Stop transmitter, Figure 6.9 serves as the user interface that controls the status of the receiver. Located on the transmitter are three toggle switches that represent the three levels of contingencies. These switches engage or disengage corresponding contacts on the receiver. Also located on the

Figure 2.1: Multi-Level Emergency Stop Transmitter

transmitter is a two-axis joystick that controls two analog outputs of the receiver.

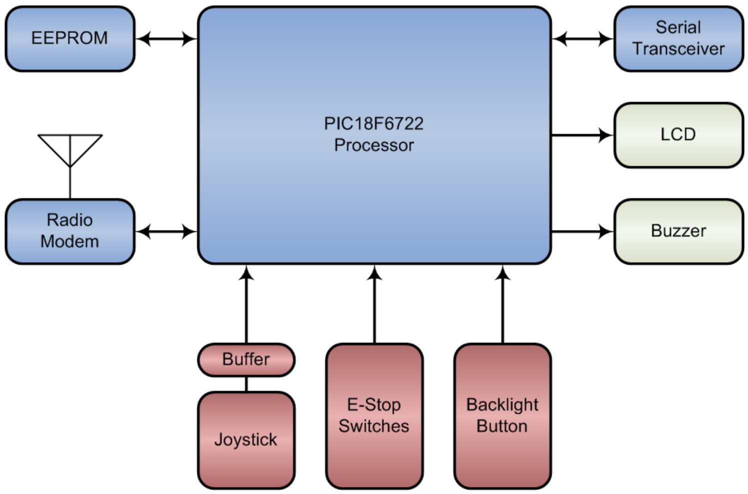

Figure 2.2: E-Stop Transmitter Hardware Block Diagram

The MLES transmitter is an embedded system centered around an 8-bit PIC Microcontroller. The microcontroller continuously monitors the positions of the toggle switches and joystick. This data is then periodically sent through a wireless radio modem to the receiver. A block diagram of the transmitter hardware design is shown in Figure 2.2.

The transmitter has several user-defined customizable settings. These settings are changed through RS-232 communications and stored in non-volatile Electronically Erasable Programmable Read Only Memory (EEPROM). To inform the user about the status of the Multi-Level Emergency Stop system, the transmitter is equipped with a graphical Liquid Crystal Display (LCD) and an audible alarm. Displayed on the LCD is the battery status of the transmitter, the wireless signal strength between the transmitter and receiver, and the status of the transmitter switches and their corresponding level contacts on the receiver. The audible alarm notifies the user of a loss of wireless communications and low battery voltage. All the components shown in Figure 2.2 are powered from an internal power supply that outputs a regulated 5V.

2.2 Power Supply

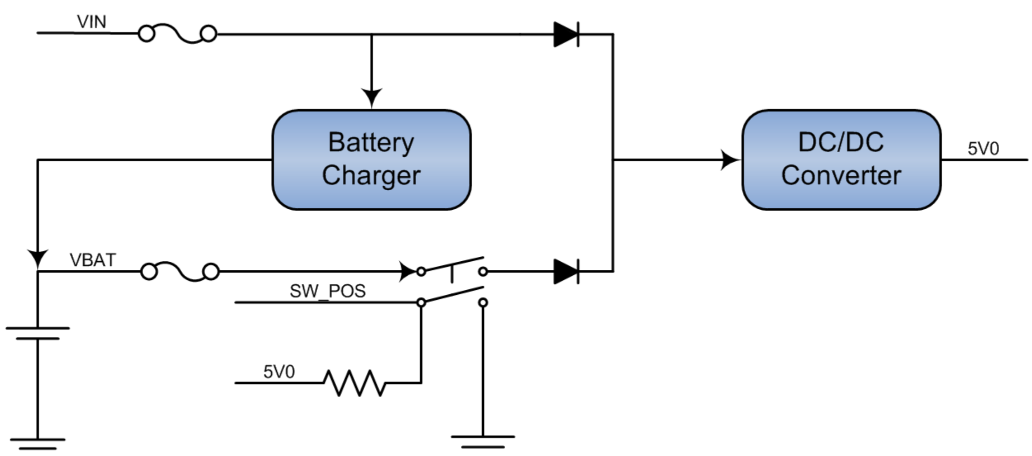

Figure 2.3: Power Supply Overview

The transmitter power supply is designed to provide a regulated output voltage to all hardware components of the transmitter from a wide range of input voltages. In order to monitor and test a vehicle's operation untethered, the transmitter is equipped with a 7.4V (nominal) rechargeable lithium polymer battery. As seen in Figure 2.3 The transmitter power supply must also accommodate an external supply of 12V (VIN) for battery charging.

The power supply is designed so that the transmitter can operate on battery power or external power while charging the battery. This is accomplished through the use of two OR-ing diodes that power the DC/DC converter from the battery or the external supply, if connected. This ensures that no load is placed on the battery during charging. The power switch, as seen in Figure 2.3, disconnects the battery from the rest of the circuit. This provides power to the hardware even when the power switch is in the off position. This allows the microcontroller to monitor the charge status when the power switch is in the off position, allowing the charge status to be displayed on the LCD.

2.2.1 DC/DC Converter

Efficiency is a major concern when dealing with any battery powered device. For this reason a switched-mode converter was implemented. This type of converter offers higher efficiency than that of a traditional linear regulator that uses a resistive load to drop the input voltage to the desired output. As the name implies, a switched-mode power converter implements switched-mode semiconductor devices to transfer energy from the input to the output. There are several types of switched-mode power supplies that can either boost (step-up), step down, or invert the input voltage. The converter implemented in the Multi-Level Emergency Stop system is a step down, or buck converter. This allows the internal components to run at a regulated voltage from either the internal battery, or an external power supply.

A basic model of the buck converter can be seen in Figure 2.4. The input voltage of the buck converter is switched on and off at a controlled rate, changing the average DC voltage.

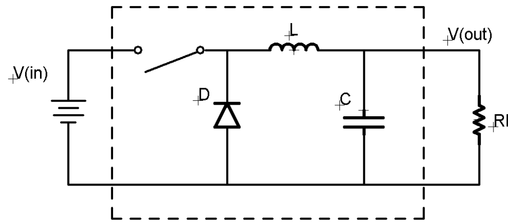

Figure 2.4: Simplified buck converter model

To understand the basic steady state functionality of the model, the circuit can be split into two sub circuits, one with the switch in the closed position, and the other when the switch is open. When the switch is closed, the diode, D, is reversed biased by the input voltage, and is essentially an open circuit. In this state, the current through the inductor will rise linearly when the switch is closed. With the switch open, the diode becomes forward biased, conducts, and the current through the inductor decreases.

The position of the switch is alternated at a fixed frequency resulting in a periodic output. The duty cycle, D, of the periodic output of the switch is set by the amount of time that the switch is in the closed position. The DC component of the output voltage is then given as the average value of the periodic waveform: DV_{in}. The resulting output voltage is proportional to the duty cycle D. The inductor, L, and capacitor, C, serve as a low-pass filter that smooths the output voltage to its DC component [3].

The actual buck converter implementation used in the emergency stop transmitter is shown in Figure 2.5. The converter includes the L5972 IC switching con-

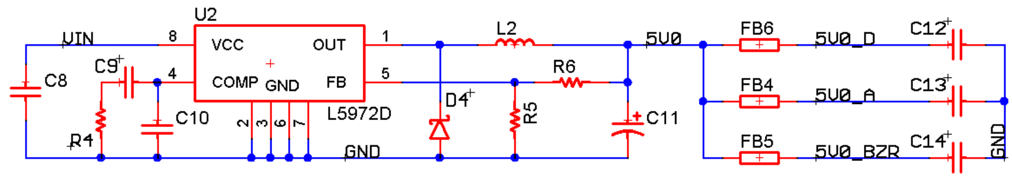

Figure 2.5: DC/DC Converter Schematic

troller in a buck converter configuration. The L5972 internally contains a switch, realized as a P-Channel MOSFET, an internal oscillator that fixes the switching frequency at 250kHz, as well as a control system that regulates the output voltage with feedback provided through an external resistor divider network. The output voltage is calculated from the following equation.

$$Vout = 1.235\left(1 + \frac{R6}{R5}\right)$$

The voltage at the feedback pin is compared to the internal reference of the L5972, and the output is set accordingly. The frequency control is set through an external compensation network attached to the COMP or compensation pin. The values used are those recommended by the datasheet. They provide stable frequency control of the system [9]. The output filter is comprised of inductor $L2$ and tantalum capacitor $C11$ (Figure 2.5).

The regulated 5V output is separated into several circuits in an attempt to isolate the analog circuitry from the digital. The constant switching between logic low and logic high levels of digital circuitry produces voltage ”spikes” or transients. These transients can effect the operation of other parts of the circuit causing unexpected results in the analog circuitry. For this reason, ferrite beads

($FB1, FB2, FB3$) were used in conjunction with ceramic capacitors to isolate digital circuitry from analog circuitry. The ferrite beads suppress high frequency noise, reducing the unwanted noise seen in the analog circuitry produced from the digital circuitry. A separate circuit was also given to the buzzer because of the inductive load of the speaker and the high voltage transients that are generated by the switching of the inductive load (see Section 3.3.1).

2.2.2 Battery Charger

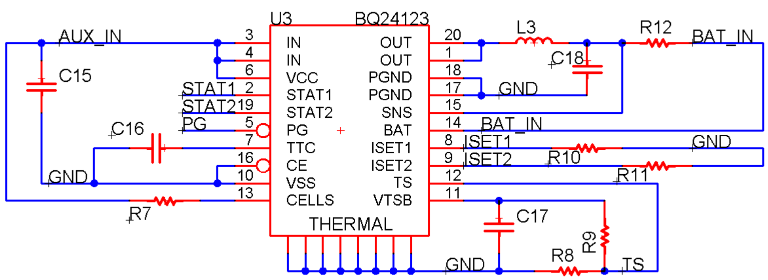

Figure 2.6: Lithium Polymer Charger Schematic

The Multi-Level emergency stop transmitter is equipped with a lithium ion battery charger that charges the internal battery from an external DC supply. The battery charger is a switched mode power supply similar to that described in Section 2.2.1 that is tailored to the strict charge requirements needed for charging a lithium polymer battery. The charge profile followed is shown in Figure 2.7. Based on the voltage of the battery, the current and voltage applied to the battery is varied according to the charge profile.

The charge profile implemented in the battery charger consists of three charge stages: precharge phase, current regulation phase, and voltage regulation and charge termination phase. The precharge phase is entered if the battery voltage is below a certain threshold, VLOW. In this phase, a precharge current is applied to the battery pack to revive deeply discharged cells. This value is determined by resistor $R11$ (Figure 2.6), and is set to .1 Amps. The current regulation phase charges the battery at a fixed current until the battery voltage of 8.4V is reached, which is the voltage of a fully charged two cell lithium polymer battery. The charge current is set by resistor $R10$ and is set at 1A. The charge termination phase is the final step in the battery charging phase. In this phase, the voltage is fixed at 8.4V, while the charge current is dropped to the precharge current.

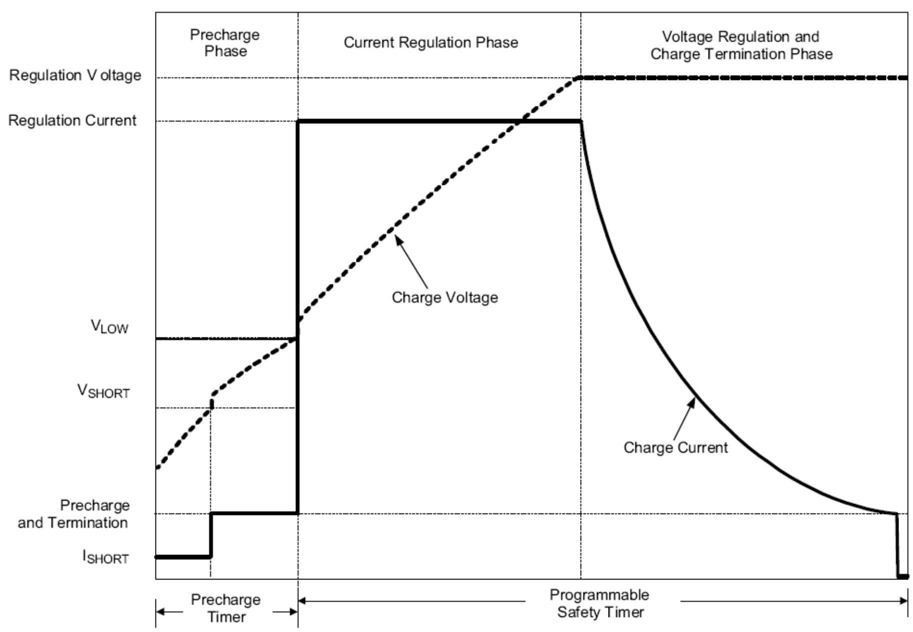

Figure 2.7: Lithium Charge Profile [10]

2.2.3 Battery Protection Circuitry

To ensure that the Multi-Level Emergency Stop system is protected against potential battery failure, several precautionary measures were taken. The internal lithium polymer batteries have the potential to ignite or explode when used improperly. For this reason, several layers of protection were designed into the transmitter hardware to prevent such events from happening.

Built into the battery charger are several layers of protection. These include overcurrent and thermal protection. The battery charger also monitors the temperature of the battery pack through a thermistor installed on the pack itself. If the temperature limit is exceeded during charging, the charge cycle is terminated. The battery charger also contains a timer that limits the maximum allowable time a battery can be charged. This timer is set to allow a maximum charge time of eight hours. In the event that the battery is not fully charged in the alloted time, the charge will terminate, and an error message is displayed on the transmitter LCD. This timer is set with capacitor $C16$ in Figure 2.6.

The high side battery terminal is also fused on the transmitter PCB to protect the batteries from unusually high current draws during operation. The battery pack chosen also has built-in protection circuitry that prevents the battery from both overvoltage and undervoltage conditions.

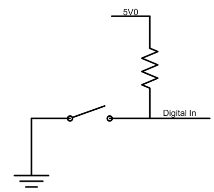

Figure 2.8: Estop Switch Schematic

2.3 Microcontroller

At the core of both the Multi-Level emergency stop transmitter and receiver is the PIC18F6722 8-bit microcontroller. The PIC18F6722 offers high digital I/O capacity and a multitude of integrated peripherals. The PIC18F6722 comes in a 64-pin TQFP (Thin Quad Flat Pack) package, with an available 54 digital I/O lines, 16-channel Analog-to-Digital converter, two Universal Asynchronous Receiver/Transmitters (UART), and two Master Synchronous Serial Ports (MSSP). This processor is also equipped with four timers, external interrupts, and a watchdog timer [7]. Figure 2.9 shows the block diagram for the PIC18F6722 series of microcontrollers.

Five digital I/O lines of the processor are responsible for monitoring switch positions. The three emergency stop level switches, power switch, and backlight switch are all monitored in a similar fashion. These switches are connected using a pull up resistor. In this configuration (see Figure 2.8). In the event of a loose connector, or broken wire, the circuit will appear as an open circuit, resulting in a safe failure mode where the emergency stop is activated.

A large portion of the digital I/O lines of the processor are claimed by the

LCD, or Liquid Crystal Display. The LCD provides the user with feedback on the status of the emergency stop system. This 128x64 pixel graphical display is controlled with the KS0108B LCD controller and requires 14 digital lines for proper operation.

2.3.1 A/D Converter

The PIC18F6722 is equipped with a 10-bit 16-channel successive approximation analog-to-digital converter (A/D). This type of converter is commonly used in microcontroller applications [1]. Converting one bit at a time, starting with the most significant bit, a successive approximation A/D requires a minimum of one clock cycle for every bit of resolution.

Although the A/D is capable of 10-bits of resolution, only 8-bits are utilized. This is done to simplify communications between the transmitter and receiver. As discussed in Section 4.1 the communications protocol from the transmitter to the receiver consists of 4 bytes. Two of these bytes are the 8-bit analog signals read from the joystick axes.

In addition to the two joystick axes, the battery voltage is read through the integrated A/D converter. The battery voltage is used to approximate the remaining battery life of the transmitter. The battery discharge curve for a lithium polymer battery, unlike other battery chemistries, is relatively linear with respect to the battery voltage. For this reason, voltage feedback provides adequate information on the remaining battery life. The remaining battery life is displayed as a battery icon in the upper left corner of the LCD screen.

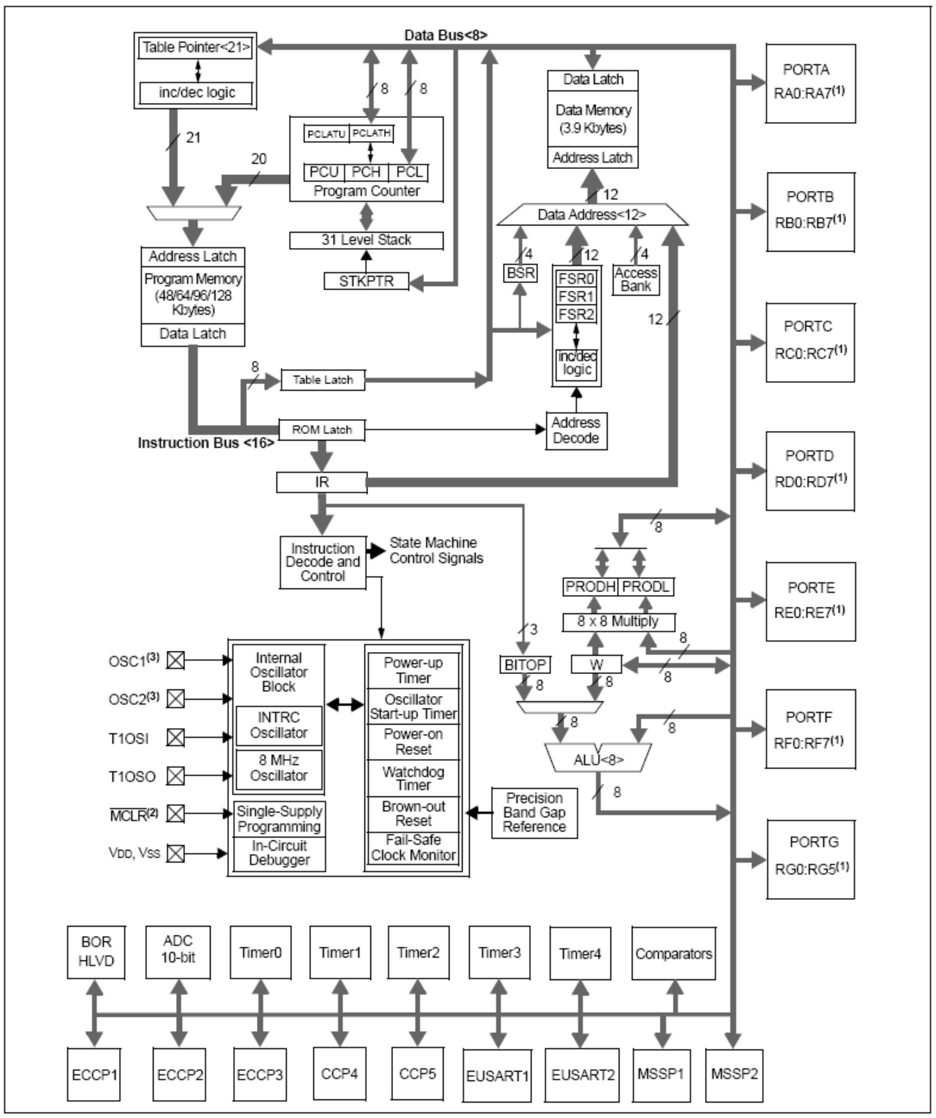

Figure 2.9: PIC18F6722 Block diagram [7]

The radio modems implemented in the Multi-Level Emergency Stop are equipped with a signal strength indicator. The signal strength is output from the radio modem as a PWM signal. To simplify the software, this signal was connected to a low-pass filter and read in as an analog voltage. The low pass filter has a cutoff frequency of $\frac{1}{2\pi RC}$. The frequency of the PWM output is 120.2Hz. The low pass filter has a cutoff frequency of less than 1Hz, which is significantly lower than the PWM output frequency to provide adequate filtering and a smooth DC output.

2.3.2 UART

There are two Universal Asynchronous Receiver/Transmitters (UART) integrated in the PIC microcontroller. The UART is a full duplex serial interface that is capable of asynchronous communication. For successful communications, there must be a UART on both ends of communicating devices. Without clock synchronization, the two communicating devices must be set to identical baud rates for successful communications [6].

The UARTs in the microcontroller are used for wireless communications to the radio modem, and communications to a host PC. The UART1 in the PIC18F6722 microcontroller is connected directly to the UART of the radio modem. The baud rate is set at 4800bps. This allows the radio to communicate wirelessly at 9600bps without overflowing the buffers or requiring flow control.

UART0 of the microcontroller is connected to a serial transceiver for communications with a computer. The TTL logic levels of the UART internal to the microcontroller must be level shifted for communications with the higher voltage requirements of a computer. This is done with a MAX3223 level transceiver. When connected to a computer, UART0 allows for firmware updates through the use of a bootloader. The MLES system can also be customized for each specific application through the serial connection and a terminal window. The bootloader and the terminal interface is set at 115200bps, allowing for fast data transfer at a standard baud rate that is compatible with most terminal programs.

2.3.3 I^{2}C

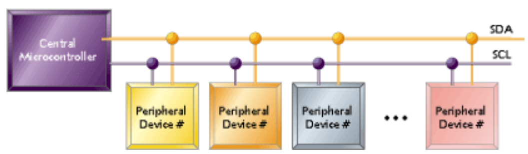

Figure 2.10: I^{2}C Bus Configuration

The PIC18F6722 is also equipped with two Master Synchronous Serial Ports (MSSP). These serial ports are used for communication with peripheral devices. The MSSP ports can operate in one of two modes: Serial Peripheral Interface (SPI) or Inter-Integrated Circuit (I^{2}C). The Multi-Level Emergency Stop transmitter uses only one of these ports in the I^{2}C configuration. This port is used to communicate with two EEPROMs. The EEPROMs provides a non-volatile memory to store user settings, and graphics that are displayed on the LCD.

The I^{2}C bus is a two-wire bus with a serial data line (SDA) and a serial clock line (SCL) [6]. The microcontroller is configured as an I^{2}C master device that communicates with the EEPROMs by addressing each devices unique address.

A standard I^2C bus configuration can be seen in Figure 2.10. The number of peripherals is limited by the number of user settable address bits. In the case of the 24LC256 EEPROM, there are three user selectable address bits for a total of 8 chips on each bus.

Chapter 3

Receiver Hardware Design

3.1 Overview

In addition to the transmitter, the other primary component to the Multi-Level Emergency Stop system is the receiver (Figure 3.1). The receiver is designed to be mounted on the unmanned vehicle being operated. Communications to the receiver are accomplished through a wireless link to the transmitter. Internal to the receiver are relays and analog outputs that are controlled through the switches and joystick located on the transmitter.

The underlying functionality and hardware design of the MLES receiver is similar to that of the transmitter. The receiver and transmitter both contain an

Figure 3.1: MLES Receiver

identical processor, radio modem, and EEPROM. The focus of this section will be on parts specific to the receiver that have not already been mentioned in the transmitter hardware design (Section 2). A hardware block diagram of the receiver can be seen in Figure 3.2.

3.2 Power Supply

Unlike the transmitter which contains an internal battery, the receiver is solely powered from the host vehicle. This eliminates the need for a battery charger in the receiver, although a DC/DC converter to regulate voltages for powering internal components is still required. The DC/DC converter used in the receiver is identical to that of the transmitter.

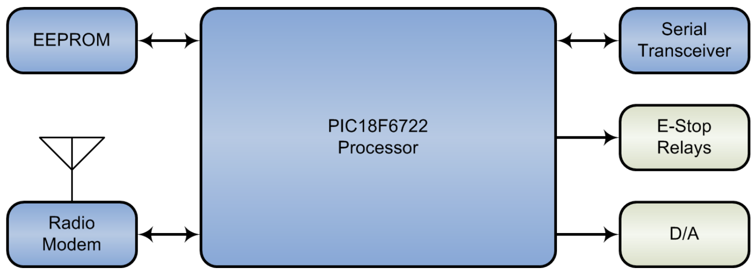

Figure 3.2: Emergency Stop Receiver Hardware Overview

3.2.1 Protection Circuitry

The MLES receiver is powered by the host unmanned vehicle being operated. This requires the end user to correctly supply power. To avoid damage to internal components of the receiver in the event of operator error, reverse polarity protection was implemented. Reverse polarity protection prevents damage to the receiver's internal components if the polarity is switched on the power inputs. As seen in Figure 3.3 the reverse polarity protection is simply a p-channel MOSFET. The drain of the transistor is connected to the positive input and the gate is connected to the negative input.

During proper operation, a positive voltage is applied to the drain of the MOSFET while the gate is connected to the ground terminal. In this configuration, the gate voltage Vg is less than the threshold voltage, and the transistor conducts. In the event that the polarity was switched to the receiver, Vg would be greater

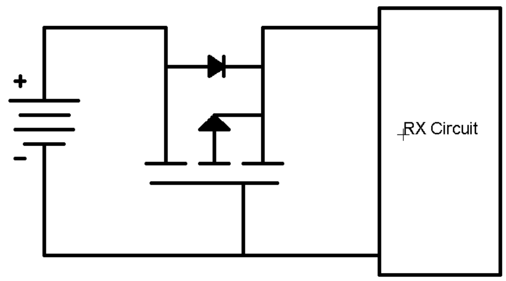

Figure 3.3: Reverse voltage protection circuit

than the threshold voltage, placing the transistor in cutoff mode. While in cut-off, the transistor acts as an open circuit, preventing any damage to the internal components. This method of circuit protection does not require any service to the receiver in the event of a reverse polarity situation unlike a conventional fussed solution.

3.3 Vehicle Interface

The Multi-Level Emergency Stop receiver links the MLES transmitter to the host vehicle through a series of vehicle interfaces. The vehicle interface of the receiver is designed to accommodate a wide variety of host vehicles. Each of the three levels of the MLES system can connect to a vehicle through high current outputs and logic level outputs. The receiver is also equipped with analog outputs that are controlled through the joystick on the transmitter. For vehicles without the capability to measure the digital or analog signal, an RS-232 serial port outputs the status of the switches as well as the position of the joystick.

3.3.1 High Current Outputs

The high current outputs of the receiver are implemented with power relays capable of interrupting loads up to 8A. The schematic of each output is shown in Figure 3.4. Shown in the schematic, relay K101 is a DPDT relay with a 5VDC coil. One of the poles is wired to a connector for a high current output, and the other pole is used for digital outputs. The center relay pin is fused at 7.5A to prevent high current loads from fusing the relay contacts together.

Each relay is controlled through a digital output of the PIC microcontroller. Limited to 25mA per output, the microcontroller is not capable of suplying the 80.6mA needed for proper coil activation. To amplify the current out of the microcontroller, a npn bi-polar junction transistor (bjt) was used (Figure 3.4). The transistor acts as a switch that turns on whenever the base emitter junction is forward biased. In this configuration, the base current, or current sourced by the processor is a fraction of the actual current needed to power the relay.

If an inductive load is switched rapidly, as is the case with the relay coil, care must be taken to suppress voltage transients. The voltage across an inductor is given by

$$v = L\frac{di}{dt}$$

where L is the inductance, i is the current, and v is the voltage. When the load across the relay coil is interrupted, the relay is turned off. The time that it takes the transistor to turn off, dt, is very small. This results in a very high voltage spike that can severely shorten the life of the switching transistor, as well as cause unwanted transients that can be seen by the entire circuit. One method of protection against this type of transient is to place a diode across the inductor coil as seen in Figure 3.4. When the transistor is turned on, the relay is activated and the diode is reversed biased. When the relay is turned off, the voltage across the inductor causes the diode to be forward biased, and the collector of the transistor is now a maximum of one diode drop below V+ [2].

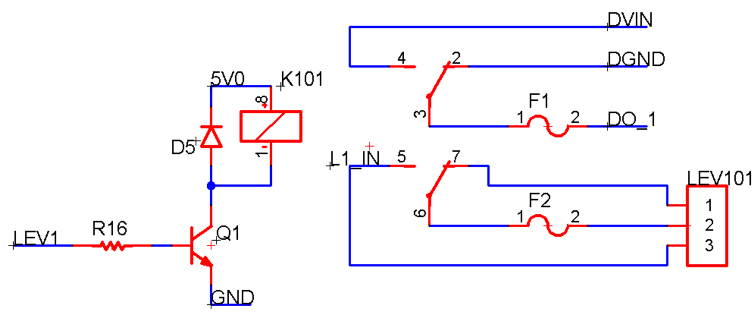

Figure 3.4: High Current Relay Output Schematic

3.3.2 Digital Logic Outputs

In addition to high current outputs, there are also digital outputs that are intended to communicate with a vehicle's data acquisition system. These digital outputs can provide information to a vehicle's on-board data acquisition system about the state of the receiver levels. As shown in Figure 3.4 the digital outputs are connected to one pole of the double pole switch, and the analog outputs are connected to the remaining pole. To reduce connector count and to simplify external wiring, all three digital outputs are fed to a single connector. The five pins are for connection of a digital supply, digital ground, and three digital outputs.

3.3.3 Analog Outputs

The position of the joystick on the transmitter is mapped to two analog outputs on the receiver. Each axis position of the joystick is sent wirelessly from the transmitter to the receiver. Upon receiving the joystick data, the appropriate calculations are made to the data based on the user-defined joystick options (Section 5.2). Once the joystick data is calculated, it is sent to a Digital to Analog Converter (DAC) where it is converted to an analog voltage.

The receiver implements two 8-bit DACs, the same resolution used to convert the joystick data on the transmitter. The simplified digital to analog converter schematic can be seen in Figure 3.5. Each output implements a MAX517 converter that communicates with the microcontroller over the I^2C bus. The MAX517 was chosen for their low cost and I^2C interface. With a slew rate of $1V/\mu S$, the speed of these converters is more than adequate for MLES.

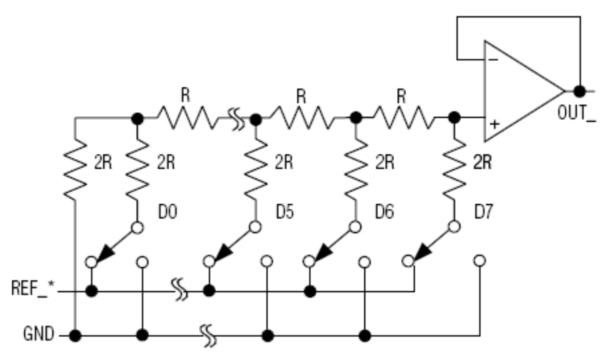

Figure 3.5: Simplified Digital to Analog Converter [12]

3.3.4 Serial Output

In addition to the analog and digital outputs, the Multi-Level Emergency Stop is equipped with an RS-232 interface. Level status and joystick position can be read serially at 38400bps. This serial link provides another possible interface for vehicles that do not have a data acquisition system or the capability to read digital or analog inputs. The data obtained through the RS-232 link is identical to that of the digital and analog outputs only in a serial format.

There are four bytes sent over the receiver's serial port. These bytes include the status of the relays and the joystick position followed by a checksum. The data is comma separated, and followed by a new line character in the following format: RELAY_STATE,X_AXIS,Y_AXIS,CHECKSUM$< cr >< lf >$.

Table 3.1: Receiver Serial Message Protocol

Byte	**Format**	**Comments**
Relay_State	10110ABC	A - Level I B - Level II C - Level III 0 = Activated 1 = Deactivated
Analog_A	0 - 255	Values Depend on Analog Settings
Analog_B	0 - 255	Values Depend on Analog Settings
Checksum	0 - 255	Exclusive OR Relay_State, Analog_A, Analog_B

Chapter 4

Wireless Communications

Wireless communication between the MLES transmitter and receiver is accomplished through the use of 900Mhz radio modems. The 9XTend OEM RF Module from Maxstream is a 1W frequency hopping spread spectrum serial radio modem. A complete Multi-Level Emergency Stop system incorporates two 9XTend radio modems, one in the transmitter, and one in the receiver.

As shown in Figure 4.1 the Xtend radio modems are capable of bi-directional communications [11]. The XTend radio modems communicate with the host PIC microcontroller through a TTL level asynchronous universal serial port. The serial interface of the radio modems act as a wireless serial cable. While there are a multitude of possibilities for wireless communications, and a near infinite choice

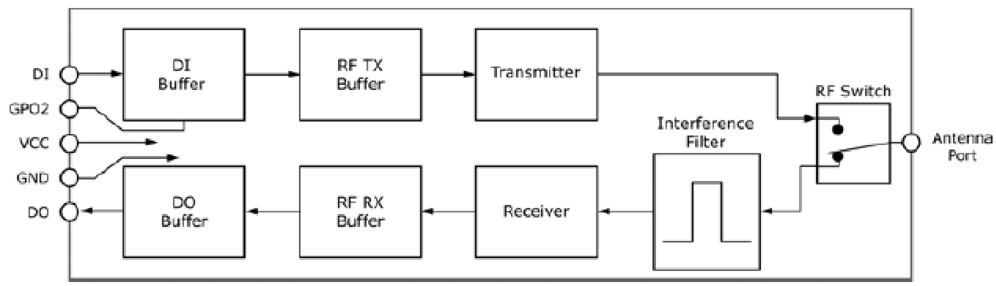

Figure 4.1: Block Diagram of 9XTend Radio Modem [11]

of transmit frequencies, the 9XTend radio modems are an ideal solution for the Multi-Level Emergency Stop system.

Designed as a safety device for unmanned vehicles, the Multi-Level Emergency Stop needed to remotely control the status of a vehicle's safety system. The operating distance of this system needed to be far enough as not to limit the capabilities of the vehicle. An aerial vehicle, for example, could operate several hundred yards away from a ground control station. A ground vehicle on the other hand may operate fairly close to the controlling base station, but in an urban environment, where a clear line of site between receiver and transmitter may not be available. Given these circumstances, a fairly high powered transmitter was needed. The XTend radio modems can be programmed to transmit at up to 1 Watt, with an idealized line of site range of 14 miles.

The serial interface to the modem from the microprocessor and the wireless transmission interface have software selectable baud rates to accommodate a variety of applications. To achieve the maximum receiver sensitivity of -110dBm, the wireless interface data rate is set at 9600bps. This is much slower than the radio modem's capabilities, but this allows for higher receiver sensitivity which translates to greater range. The other possible wireless interface rate is 115200bps. In this setting, the receiver sensitivity is set at -100dBm. The data rate from the host microprocessor to the radio modem is set at 4800bps or 9600bps depending on the wireless interface setting and operation mode (see Section 5) of the Multi-Level Emergency Stop system.

Another advantaged offered by the XTend radio modem is the CRC or cyclic redundancy check. The CRC verifies the integrity of the data sent over the wireless link. When dealing with wireless communications, signal degradation is a major concern. The CRC ensures that the data passed between the transmitter and the receiver will be the correct data with a high level of certainty. Each packet sent is appended with a CRC byte. When the packet reaches its destination, the receiver also calculates a CRC byte. If the CRC bytes match, then the data is sent to the host microprocessor. If they do not, the data is discarded. Having this integrated into the radio modem eliminated the need to implement a CRC on the host microprocessor, reducing software complexity while ensuring, with a high degree of certainty, that the data received by the microprocessor is the correct data.

There are some precautions that must be taken when using off the shelf radio modems. Since these can be readily purchased, the communications is vulnerable to outside intrusion and attacks. To prevent this, the XTend radio modems offer several layers of security. Each packet transmitted contains addressing information that is used to ensure that the incoming data is received by the intended recipient. As seen in Figure 4.2 the receiving module inspects each packet's ven-

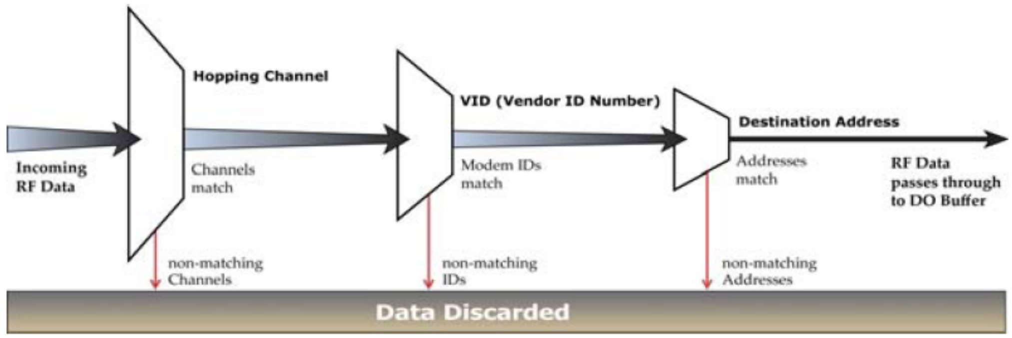

Figure 4.2: Filtration information contained within each RF packet header [11]

dor identification number, and the destination address. If these parameters are not identical to those of the receiver module, then the packet is discarded. Each modem can be configured with one of 32750 unique vendor identification numbers, and 65536 programmable destination addresses. While there are billions of possible specific modem configurations, having many units operating simultaneously can cause interference, resulting in reduced range and data rates. The spread spectrum functionality of the radio modems allow multiple units to operate with minimal interference by allowing each unit to operate on a separate hopping channel.

4.0.5 Spread Spectrum Communications

A conventional narrow-band wireless signal transmits data in a very narrow bandwidth. As a result of this narrow frequency, such communications are prone to interference [5]. A single interfering signal operating at or around the narrow-band frequency can severely hinder communications. The Multi Level Emergency Stop system requires a reliable wireless signal that is resistant to interference. Spread spectrum communications takes a signal to be transmitted and spreads that signal over a much larger bandwidth than that of a narrow-band signal.

Maxstream XTend radio modems employ a FHSS, or Frequency Hopping Spread Spectrum communications protocol. This technique employs a pseudo random sequence to switch frequencies that is known by both the transmitter and receiver. A simple example of a FHSS sequence can be seen in Figure 4.3. In this example, the five frequencies used follow the sequence 4,1,5,3,2. At each time step, the frequency of transmission is changed. For this reason, the receiver must also follow the same hop sequence to receive data. This synchronization is done internally by the modems by setting one of the ten hopping channels that share 50 frequencies in the range of 902-928MHz.

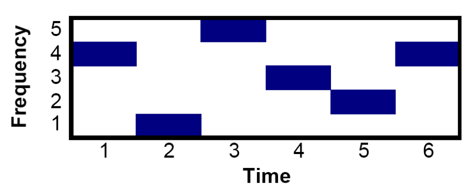

Figure 4.3: Frequency Hopping Spread Spectrum pseudo random sequence example [8]

By spreading communications over a large bandwidth, interference, or unwanted communications on individual frequencies do not have a large effect on the overall performance of the system. In addition to interference resistance, spread spectrum communications also offer an added layer of security. The FHSS communications allow for multiple MLES systems to operate simultaneously in the same area with little interference to each other. The 10 hop sequences offered by the XTend modems allows for up to 10 units to operate in the same area with minimal interference.

4.1 Wireless Protocol

The multi-Level Emergency Stop implements bi-directional communications between the receiver and transmitter. Figure 4.4 shows the wireless communications protocol of the MLES. The transmitter sends the position of the level switches and the joystick position to the receiver followed by a checksum. Upon receiving data, the MLES receiver calculates a checksum and compares it against that sent by the transmitter. If the data is valid and the calculated checksum matches the transmitted checksum, the relays and analog outputs are updated acordingly. Once the status of the relays are updated, the receiver sends the current relay state back to the transmitter where it is displayed on the LCD.

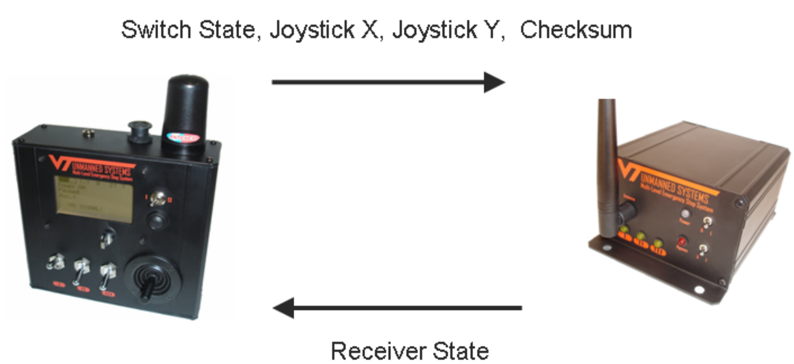

Figure 4.4: Wireless Protocol

Chapter 5

Software Design

The Multi-Level Emergency Stop receiver and transmitter each have unique software, or firmware, that is embedded on their corresponding microcontroller. The firmware controls the operation of the microcontroller by reading the status of switches, collecting data from the radio modems, and transmitting data.

The MLES system is versatile and can adapt to a multitude of unmanned vehicle requirements. Each unique application of the MLES requires parameters within the firmware to be modified by the end user. To accomplish this, the firmware is designed with a command mode user interface. Available on both the transmitter and receiver, the command mode allows for complete customization of the system. This user interface allows each emergency stop system to run identical firmware while allowing application specific user settings.

5.1 Transmitter Command Mode

There are several software settable configuration options allowed through the MLES transmitter firmware. These options allow the user to change operating modes, labels displayed on the LCD, and wireless communication settings. Table 5.1 shows the menu for the transmitter command mode.

Table 5.1: TX Command Mode Main Menu

```
***********TX COMMAND MODE***********
1: Operation Mode
2: RF Communications Settings
3: Change Labels
4: Restore Defaults
5: Display Current Settings
e: (e)xit Command Mode
%>
```

There are two main operating modes of the MLES. Depending on the application, the MLES can be optimize to maximize range or to minimize latency between transmitter and receiver. The OPERATION MODE menu is seen in Table 5.2. Changing operating modes alters the wireless data rate at which the transmitter and receiver communicate.

As described in the wireless communications section (Section 4), the radio modems implemented in the Multi-Level Emergency Stop can be set to communicate at two different baud rates. At the slower baud rate (9600bps), the receivers sensitivity is increased compared to the sensitivity of the faster data rate (115200bps). This increased sensitivity translates to a longer range of the MLES system, while the slower communications result in a slower response time.

Table 5.2: TX Operation Mode Menu

```
***********OPERATION MODE***********
1: Low Latency
2: Long Range
e: (e)xit to main menu
%>
```

While a response time of several hundred milliseconds is acceptable when dealing with the discrete emergency stop levels in most applications, this may not be the case when implementing the analog joystick, especially for vehicle control. For this reason, a low latency mode was implemented. The wireless transmission rate in the low latency mode is 12 times that of the long range mode. Transmitting a 115200bps as opposed to 9600bps in long range mode, the latency is reduced from hundreds of milliseconds to tens of milliseconds.

The CHANGE LABELS command allows the labels displayed on the LCD that correspond to each level to be customized for each unique implementation. This customization allows for an operator of the MLES system to easily determine the state of the system and the function of each level. Each switch, or level, is associated with two labels: one when the switch is in the up position, and the other when the switch is in the down position.

The MLES also allows a user to modify the wireless communications settings through the RF COMMUNICATIONS SETTINGS option in the main menu (Table 5.1). The settings that are software selectable by the user are the hopping channel, vendor identification number, and destination address as described in Section 4. The communications settings user interface is seen in Table 5.3. By setting the vendor identification, hopping channel, and destination address of the system, a user can assign a transmitter and receiver to communicate with each other.

Table 5.3: TX RF Settings Menu

```
***********RF COMM SETTINGS***********
1: Transmit Power Level
2: Vendor Identification Number
3: Hopping Channel
4: Destination Address
e: (e)xit to Main Menu
%>
```

To conserve power, the transmit power can be adjusted through the TRANSMIT POWER LEVEL command mode (Table 5.4). For applications where long ranges are not needed, the transmit power can be changed accordingly. As a result, the battery life of the transmitter can be extended. The transmit power can also be changed on the receiver for the same reasons, although the transmit power of the receiver and transmitter do not need to be identical for proper operation.

Table 5.4: Transmit Power Level Settings

```
****Transmit Power Level Settings****

1: 1 mW
2: 10 mW
3: 100 mW
4: 500 mW
5: 1000 mW
e: (e)xit to main menu
```

5.2 Receiver Command Mode

Similar to that of the transmitter, there are receiver specific settings that can be configured through the receiver command mode. Pairing a receiver and transmitter requires the sc Operation Mode and RF COMMUNICATIONS SETTINGS to have identical values. Shown in Table 5.5 the receiver command mode also allows users to configure joystick settings and a communications timeout action.

Table 5.5: RX Command Mode Main Menu

```
***********RX COMMAND MODE***********
1: Operation Mode
2: RF Communications Settings
3: Joystick Settings
4: Communications Timeout Action
5: Restore Defaults
6: Display Current Settings
e: (e)xit Command Mode
%>
```

The COMMUNICATIONS TIMEOUT SETTINGS are customizable to provide the safest possible configurations for a particular application. A communication loss occurs when the receiver does not obtain a valid message from the transmitter for a predetermined amount of time. Several events can cause a communications timeout. One possibility would be that the vehicle is out of the transmitters range of the receiver. Another possibility is that the power to the transmitter has turned off, which can be caused by a drained transmitter battery. The communications loss menu is shown in Table 5.6.

Table 5.6: RX Communications Timeout Menu

```
**********RX Communications Timeout Settings**********

Level  I                 II                III

1:  Engaged            Engaged            Engaged
2:  Engaged            Engaged            Disengaged
3:  Engaged            Disengaged         Engaged
4:  Engaged            Disengaged         Disengaged
5:  Disengaged         Engaged            Engaged
6:  Disengaged         Engaged            Disengaged
7:  Disengaged         Disengaged         Engaged
8:  Disengaged         Disengaged         Disengaged

%>
```

Having user-defined timeout configurations are of particular importance when dealing with different types of unmanned vehicles. To better understand this functionality, a rotary winged vehicle will be considered. The three levels of contingencies can be implemented as follows: Level I - Engine shut down, Level II - Slow Descent, Level III - Controlled Hover. In the event of a communications loss of the MLES during flight, shutting the engine down of a properly functioning vehicle would be dangerous and unwise. A safer solution would be to have the vehicle maintain a hover in its current position until communications is regained, or some alternate action is taken. This situation would correspond to the setting number 2 (Table 5.6) of the communications timeout configuration: Level I - Engaged, Level II - Engaged, Level III - Disengaged.

Table 5.7: RX Joystick Settings Menu

```
****RX Joystick Settings****

1: Direct Mapped Mode
2: Mixed Mode
e: (e)xit to main menu
%>
```

The transmitter joystick is set up to control analog outputs on the receiver. The specific relation of the analog outputs to the joystick position is software selectable by the user from the receiver command mode (Table 5.7). The DIRECT MAPPED MODE maps the X and Y axis of the joystick directly to the analog A and analog B outputs on the receiver. In MIXED MODE the joystick outputs are designed to accommodate a differential or 'tank' drive vehicle. In this mode, a forward Y axis translation on the joystick results in a positive voltage on both analog outputs of the receiver. Likewise, a horizontal or X axis movement of the joystick results in an equal and opposite voltage on each output. The equation below is used to mix the joystick inputs to analog outputs A and B on the receiver. The values read from joystick are represented by X and Y, and range from 0-255.

$$A = \frac{Y}{k} + \frac{X}{j} + f$$
$$B = \frac{Y}{k} - \frac{X}{j} + g$$

Parameters k and j above correspond the X and Y axis user settable gains. These gains can be set to one of six values from the command prompt. These values are limited to powers of two in order to simplify the computational complexity. In doing so, all division operations are replaced by shift instructions, requiring fewer cycles to calculate. By default, both are set at unity gain. This allows the output of both axes to swing the entire 0-5V range centered around 2.5V. Changing the gains limits the effective range of the joystick axis. To maintain a center of 2.5V, parameters f and g are added to the appropriate axis. These parameters are calculated using the following equation. The value 128 in the above equation refers to the midpoint (2.5V) of the 8-bit digital-to-analog converters used.

$$f = 128 - [\frac{128}{k} + \frac{128}{j}]$$
$$g = 128 - [\frac{128}{k} - \frac{128}{j}]$$

The receiver and transmitter both have the ability to revert back to the factory default settings through the RESTORE DEFAULTS menu. This settings allows the transmitter and receiver to communicate with each other in low latency mode at maximum transmit power. The default settings also set the communications timeout to an all deactivated state and a direct mapped joystick mode.

5.3 TX Firmware

The transmitter firmware continuously monitors the status of the switches and joystick while transmitting their values to the receiver. The TX firmware also monitors the status of the entire MLES system, providing feedback to the user through the display. Transmitting the status of the switches and joystick is considered a time critical process. For this reason, it is separated from all other functions.

This separation is provided through the use of Interrupt Service Routines, or ISR's. Achieving deterministic periodic data transfer is critical for reliable operation of the MLES system. For this reason all data is transferred in a time triggered ISR. As the name implies, the Interrupt Service Routine interrupts the executing code and begins executing the code in the corresponding service routine. In the case of the timer ISR, the service routine is called, or triggered whenever the value of the timer overflows. This provides an accurate periodic execution for wireless data transfer.

The microcontroller used in the Multi-Level Emergency Stop system has 4 timers available that can be used to trigger an ISR. The firmware of the transmitter utilizes one of these timers, TIMER0. The TIMER0 ISR (Figure 5.1) reads the values of the joystick, battery, temperature, and signal strength from the on board A/D converter. Once read, the corresponding data buffers are updated. In addition to the analog values, the state of the switches is also read, and corresponding buffer updated. After updating the data buffers, the joystick position and the switch positions are sent to the receiver followed by an exclusive-OR checksum of the data. This process is then repeated every 71ms or 284ms depending on the operation mode.

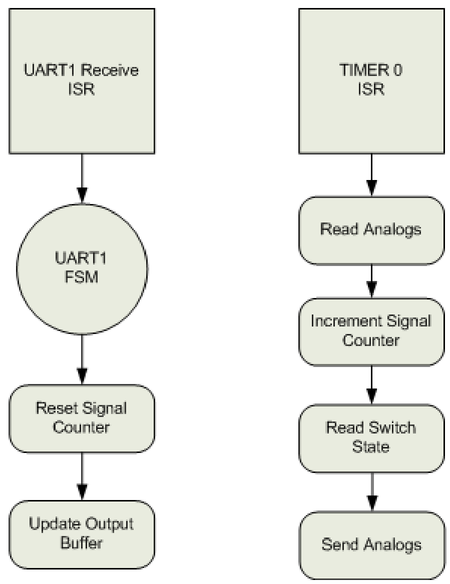

Figure 5.1: Transmitter ISR Flow Diagrams

Reading data sent from the receiver is also interrupt based. The UARTs on the microcontroller have the ability to trigger an interrupt whenever data is received in the UART buffer. Upon receiving a byte of data, the receive ISR is triggered, and that byte is then placed in a data buffer where it is continuously overwritten every time a new byte is received. This buffer is then used to update the LCD of the status of the receiver contacts.

Performed outside Interrupt Service Routines are the less critical tasks such as updating the LCD and reading the state of the backlight button. The LCD routines are called inside the main software loop as shown in Figure 5.2. This allows these less critical tasks to be interrupted whenever an ISR is triggered. Within the

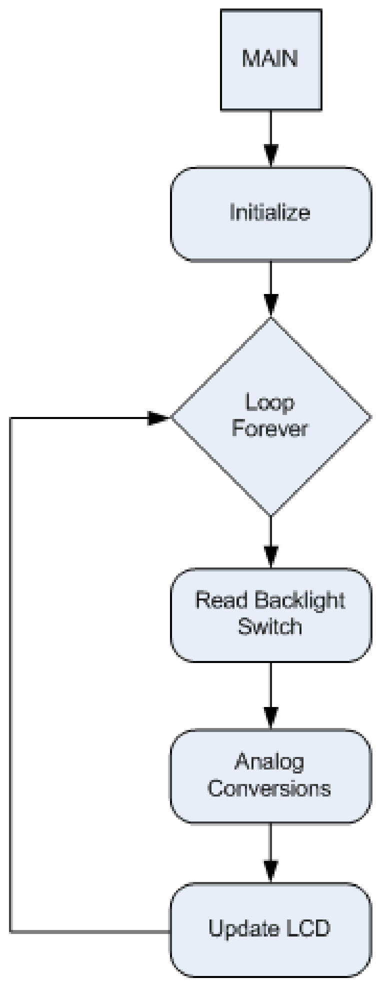

Figure 5.2: Transmitter Main Loop Flow Diagram

LCD routines, calculations are made to the values of the battery voltage and signal strength before they are displayed on screen. The voltage is displayed as a battery symbol with the battery level represented by the percentage of the battery that is colored. A similar calculation is done for the signal strength. These icons mimic that of a cellular phone, and are designed to be easily recognizable by a user. The main routine also monitors the status of the backlight switch, and turns on or off the LCD backlight accordingly.

Upon power up or a processor reset, initialization of the system occurs. This initialization includes reading the user defined values from EEPROM, setting up processor peripherals, and configuring the interrupt service routines.

5.4 RX Firmware

The functionality of the receiver's firmware is to parse and interpret the messages sent from the transmitter. This data contains information about the status of the switches and the position of the joystick. This information is sent into a finite state machine (FSM), where it is checked for validity. Once confirmed that the data received is in the correct format, and the checksum is verified, the receiver manipulates the hardware accordingly. The switch information is used to update the status of the relays, while the joystick information is used to update the analog output voltages.

The receiver software flow diagram is shown in Figure 5.3. During initialization, the user values are read into ram from EEPROM. Once initialized, the state of the bypass switch is checked. If in bypass mode, the relays are all activated, interrupts are disabled, and the processor is set in an infinite loop waiting on a reset. If the bypass switch is not engaged, the system is in run mode. In this mode, the signal counter is checked to determine if communications with the transmitter are still active. This communications counter is updated in the UART1 interrupt service routine, see Figure 5.4. If the counter is below a certain threshold, communications are still active, and the variable updated by the UART1 state machine are used to set the state of the relays. If the signal counter is above the threshold, the signal is considered lost, and the user set timeout action is invoked. This process is repeated continuously.

The ISR flow diagram is shown in Figure 5.4. These interrupt service routines are continuously running independent to the main function. The UART0 and UART1 receive interrupts are triggered every time a character enters into the corresponding UART buffer on the microcontroller. This data is then sent into a finite state machine where it is checked for validity. The TIMER0 ISR is responsible for sending the current status of the relays back to the transmitter. This allows the transmitter to display the status of the receiver relays. The timer ISR continuously runs, and the frequency depends on the operation mode. In low latency mode the the ISR is triggered every 284ms, which is how often the data is sent. In low latency mode, the data is sent out every 71ms. This is calculated by the following equation: $T_{ISR} = \frac{f_{clk}}{4}\frac{1}{prescaler}2^{16}$ Where f_{clk} is the crystal frequency of $14.7456MHz$. The prescaler is changed from 16 in long range mode to 4 in low latency mode.

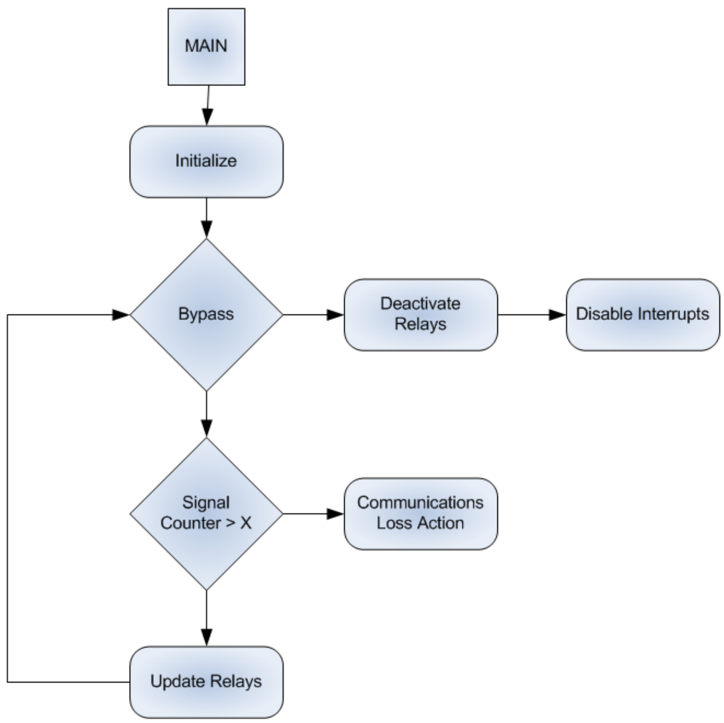

Figure 5.3: Receiver Software Flow Diagram

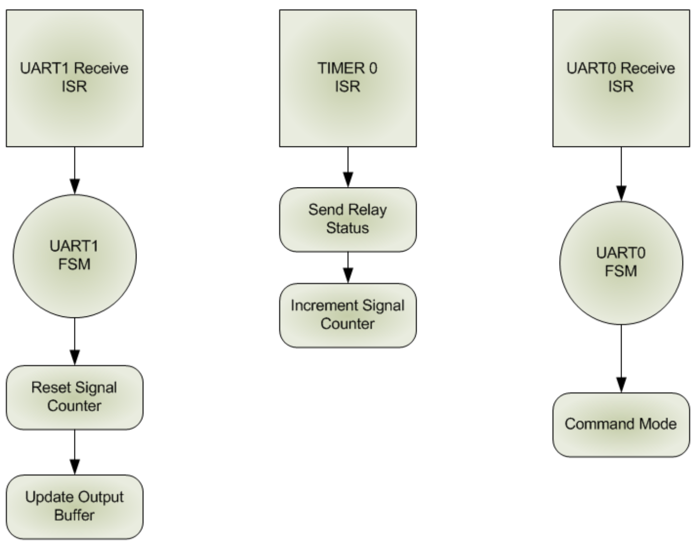

Figure 5.4: Receiver ISR Flow Diagrams

Chapter 6

Revision History

6.1 Overview

The Multi-Level Emergency Stop system has been through several revisions spanning the past two years. As one of the first projects of JOUSTER, the development of the MLES system reflects the progress and capabilities of JOUSTER since its inception. This section outlines the development history of the Multi-Level Emergency Stop system.

6.2 Version 1.0

Version 1.0 of the MLES (figure 6.1) was one of the first circuit boards designed in JOUSTER. All components used in this version were through hole components that were selected for their ease of assembly. The microcontroller used in Version 1.0 of the MLES was a 16 series PIC microcontroller. This design allowed for up to four levels of contingencies, although a full enclosed implementation of Version 1.0 was never completed. The display used was a 2x20 character alphanumeric LCD. This version also implemented an external hardware UART that required the addition of an external crystal. All components were powered with an external 5V linear regulator.

Version 1.0 was quickly replaced with Version 1.1. Version 1.1 implemented the same 16 series PIC microcontroller although the internal PIC UART was utilized with a standard serial transceiver. Version 1.1 also upgraded to a 4x20 alphanumeric LCD. Version 1.1 utilized the same PCB for both the receiver and transmitter. This required the need for an external relay board on the receiver. The packaged version of 1.1 can be seen in Figure 6.2.

6.3 Version 2.0

The driving factor leading to the development of Version 2.0 was the implementation of a higher powered 1W radio modem. Version 2.0 was a major technological advancement over the first versions. Version 2.0 was converted to mainly surface mount components with an 0805 package as the smallest sized technology. An-

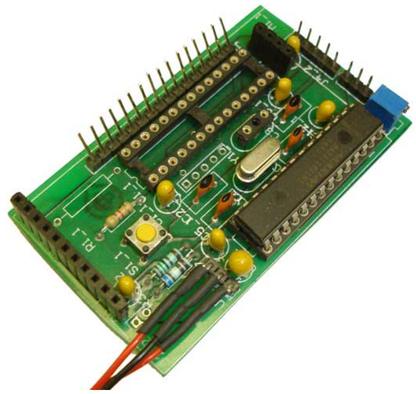

Figure 6.1: Version 1.0 of the Multi-Level Emergency Stop System

other major design change was the implementation of a buck converter to improve efficiency. Version 2.0 was also the first version that implemented a 128x64 pixel graphical LCD.

Designed around the package of the radio modem, there were no plans for an enclosure during the development. There was a single board design for both the receiver and transmitter, that ran different software for each implementation. The switch inputs on the transmitter were used as relay drivers for the receiver. The relays were housed on a separate relay board.

The original package for Version 2.0 did not include relays. This led to the development of a separate relay board that was designed around an enclosure. This relay board consisted of three relays, and had sockets to accepted the PCB of Version 2.0 (figure 6.3).

Figure 6.2: MLES System Version 1.1

6.4 Version 3.0

There were relatively few hardware changes to Version 3.0. The main hardware change to Version 3.0 from 2.0 included a pin compatible 18F4620 PIC microcontroller. The 18 series microcontrollers have a larger instruction set, and are designed to be programmed using the C programming language. Hardware changes made to Version 3.0 include a less expensive DC/DC converter and some minor routing changes.

Version 3.0 was the first version with a custom designed enclosure. Figure 6.5 shows the first custom enclosure made for the Multi-Level Emergency Stop system. The enclosure was designed using a rapid prototyping process.

Although the enclosure provided a professional look to the Multi-Level Emergency Stop system, there were several problems with its design. Constructed out

Figure 6.3: Version 2.0 of the Multi-Level Emergency Stop System

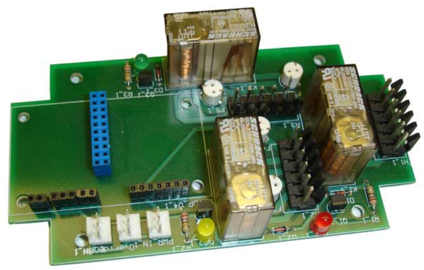

Figure 6.4: Relay Board for Version 2.0 of the MLES System

of plastic, additional shielding was needed to protect the processor from RF interference by the radio modem. This required an additional time consuming process of applying a conductive tape or paint to the interior of the enclosure. Another disadvantage of the enclosure was cost. Each enclosure cost around $300, and several weeks to produce.

Figure 6.5: Version 3.0 Transmitter MLES System

6.5 Version 4.0

Version 4.0 was the first Multi-Level Emergency Stop system that was designed with a joystick on the transmitter. Implementing the joystick prompted the need for a redesign of both the transmitter and receiver. This version was the first version to implement separate circuit boards for the transmitter and receiver.

In an attempt to solve the shielding issues of the previous versions, new enclosures were designed for the entire MLES system. The new transmitter enclosure was machined out of billet aluminum. The end product is seen in Figure 6.6, and was a very aesthetically pleasing. Although the initial cost of this enclosure was high ($750), this was to serve as a template that could easily be cast for a fraction of the cost.

The electronics of the transmitter in Version 4.0 were also the first to include an integrated battery charger. While previous versions all utilized lithium-ion batteries, they had required an expensive external charger. By integrating the charger, the overall system cost went down, and the battery charging could be done through the use of a standard power supply.

Another major modification implemented in Version 4.0 was the implementation of a PIC18F6722. This microcontroller had two UARTs as opposed to one in previous versions. With the addition of the second UART, there was a significant redesign in the systems firmware. The firmware in Version 4.0 was moved to interrupt based serial routines, as opposed to polling in previous versions.

Another major modification to Version 4.0 was the design of the receiver. Past

Figure 6.6: Transmitter Version 4.0

versions of the Multi-Level Emergency Stop had never fully developed a reliable receiver. Version 4.0 had a custom extruded aluminum enclosure (figure 6.7) designed to accommodate all receiver electronics. This new receiver design focused on reliability and ease of assembly by reducing the amount of wires. This was accomplished by board mounting all connectors, switches and LEDs. The circuit board design was divided into two boards that slid into the extruded aluminum enclosure.

Figure 6.7: Version 4.0 Enclosed Receiver

6.6 Version 5.0

Version 5.0 of the MLES system implemented a new transmitter enclosure design. Although the transmitter enclosure of Version 4.0 was aesthetically pleasing, there was no cost effective way of reproducing it in low quantities. This led to the third and final transmitter enclosure design seen in Figure 6.8. The only major hardware change, aside from the form factor, was the implementation of a toggle switch for the power. The transmitter enclosure of Version 5.0 was implemented using a standard extruded aluminum enclosure machined for the MLES, which is identical to the process used in the receiver. The final product is shown in Figure 6.9.

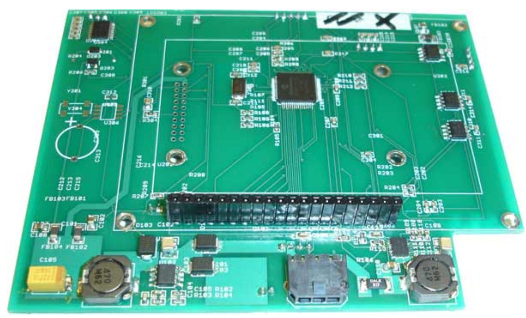

Figure 6.8: Version 5.0 Transmitter Hardware Design

Figure 6.9: Transmitter Version 5.0

Chapter 7

Analysis and Testing

7.1 Overview

The Multi-Level Emergency Stop system was tested and compared against the design criteria. Tests included power supply performance, battery charger performance, battery life, and wireless communications performance. The power supplies were tested to verify proper voltage and current requirements were satisfied. Battery life and battery charging were also tested and compared against the initial design goals. Wireless performance of the MLES system was also tested. These tests included response time or latency of the system and range performance.

7.2 Power Supply

The performance of the DC/DC converters were tested to ensure the output voltages met the requirements of the components they powered. The output voltages of three transmitters and three receivers were tested. The range of operating voltages was from 5.034 - 5.077V.

The DC output voltages of these tests meet the required component specifications. The greatest common operating range of all components of the Multi-Level Emergency Stop system is 4.5-5.5V. If the transmit power of the radio modems is set to the maximum 1 Watt, then the radio modems impose a tighter operating range of 4.75-5.5V. The DC component of all systems tested fall well within these specified operating ranges.

Also tested was the AC component of the analog supply voltage. The AC component can effect the performance of the analog to digital converters if the supply is excessively noisy. The peek to peek voltage swing of the AC component of the supply is around 20mV. This can alter the analog value at most one significant bit on an 8-bit A/D converter with a resolution of $\frac{5V}{2^8} = 19.5mV$. This has little effect on the performance of the analog to digital converters and is insignificant once these values are filtered in software.

The DC/DC were also tested for proper operation by varying the input voltage over their full operating range. The results of these tests can be seen in figures 7.1 and 7.2. The power consumption was then calculated from these results from the product of the current and voltage. Figure 7.3 shows the average power consumption of the transmitter and Figure 7.4 shows the average power consumption curve of the receiver.

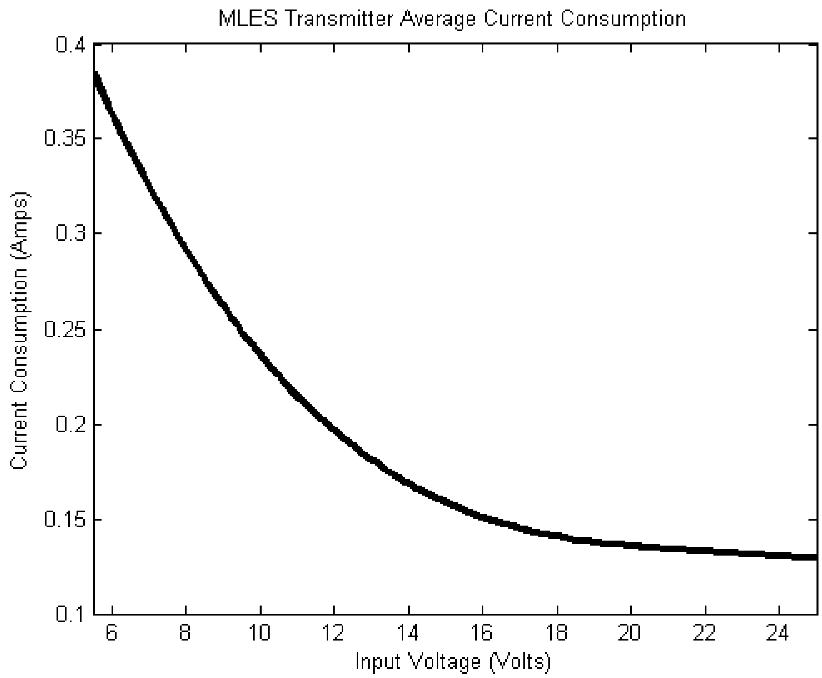

Figure 7.1: Average Transmitter Current Consumption

These results were taken with the system operating in long range mode. The receiver power consumption is higher than that of the transmitter since the receiver power consumption tests were taken with all three relays powered. The transmitter power consumption curve (figure 7.3) shows that the most efficient operating range is between 6V and 8V. This is one of the reasons that a battery with a nominal voltage of 7.4V was used.

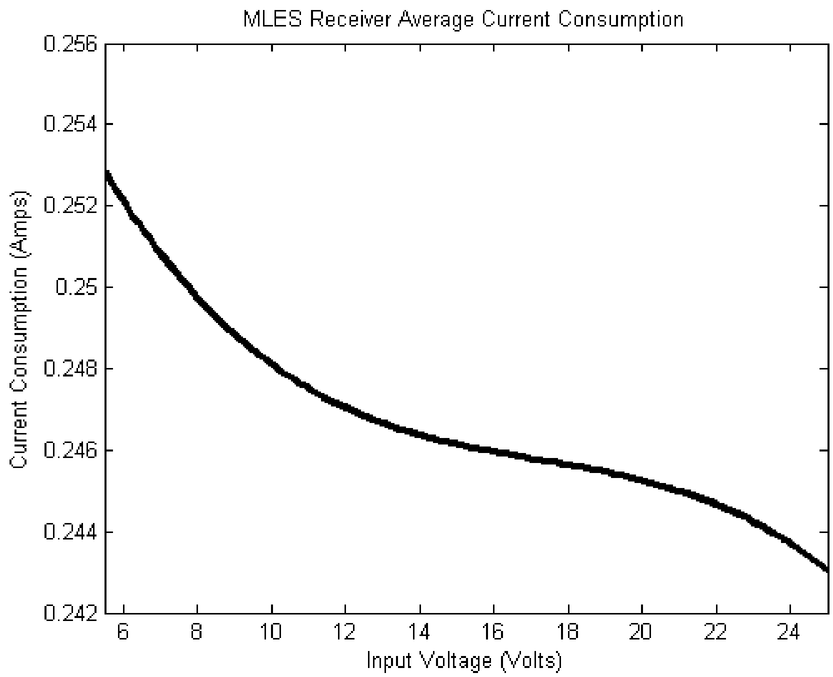

Figure 7.2: Average Receiver Current Consumption

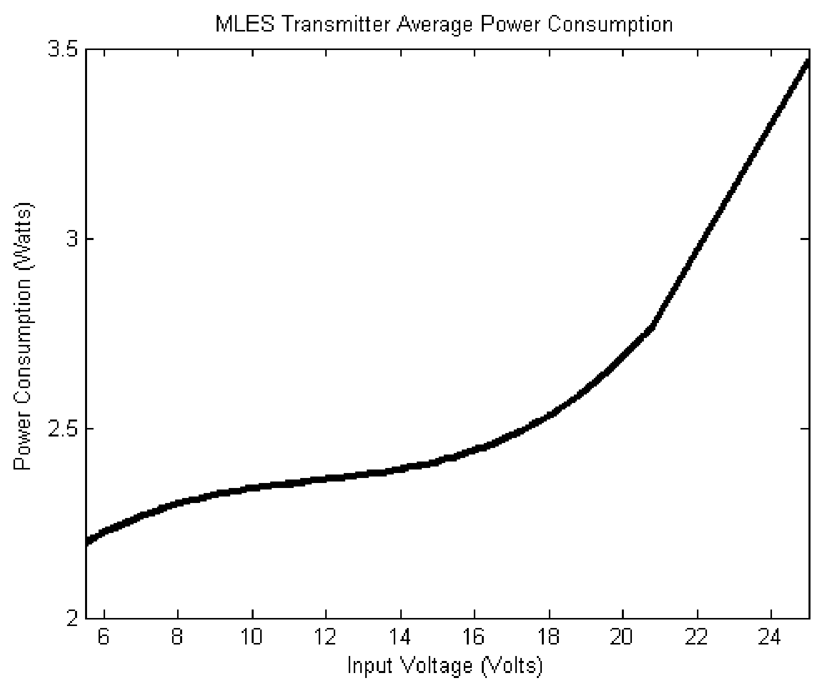

Figure 7.3: Average Transmitter Power Consumption

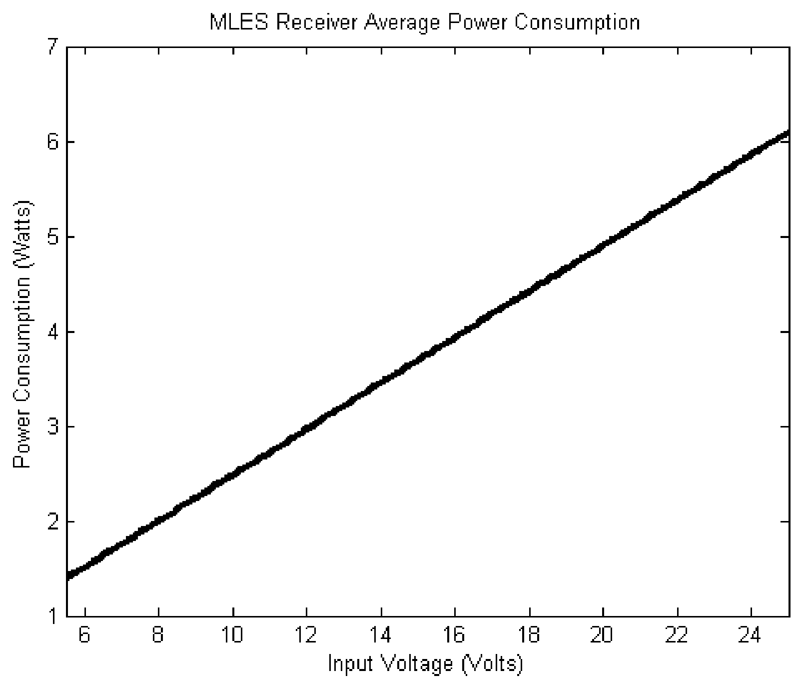

Figure 7.4: Average Receiver Power Consumption

7.2.1 Battery Charger

Tests were performed on the battery charger to verify proper charging of the lithium batteries in the transmitter. The charge current curve can be seen in Figure 7.5. This curve follows the expected charge curve of Section 2.2.2. Similarly, the charge voltage (Figure 7.6) also follows the charge curve as expected. The charge time, as seen in the charge curves, is around 5 hours.

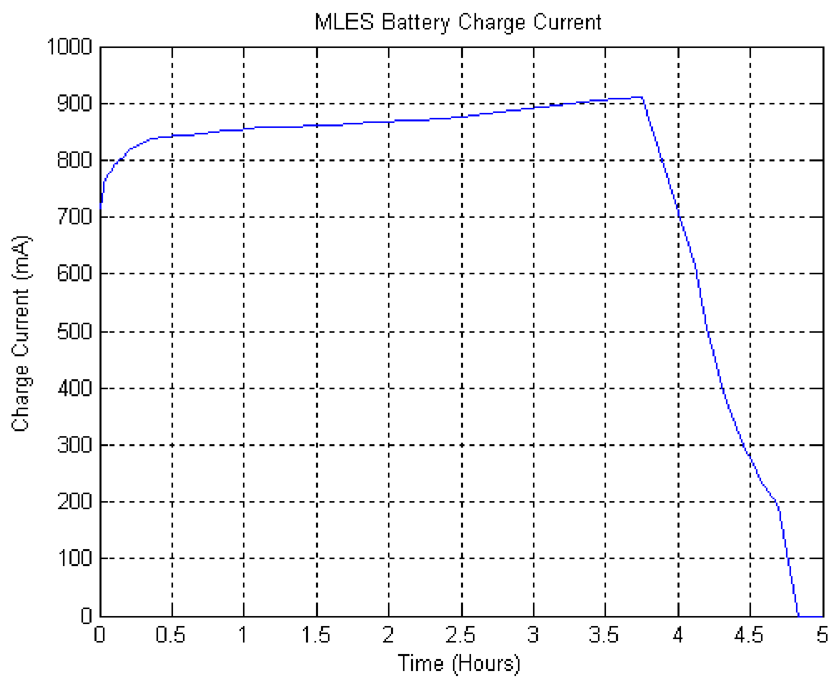

Figure 7.5: Battery Charge Current

With charge current of up to 1A, the battery charger consumes the most power of the transmitter. These relatively high currents result in significant heat dissipation. For this reason, the temperature of the transmitter was monitored during the entire battery charge cycle to ensure stability of the system. Figure 7.7 shows the

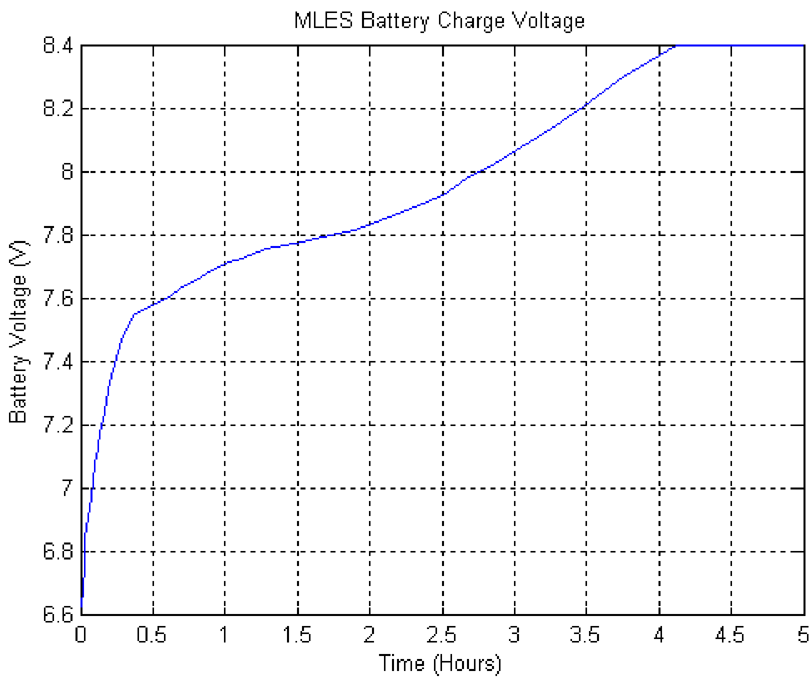

Figure 7.6: Battery Charge Voltage Curve

thermal performance of the charger during a charge cycle. The tests show that the maximum temperature reached is around 68°C.

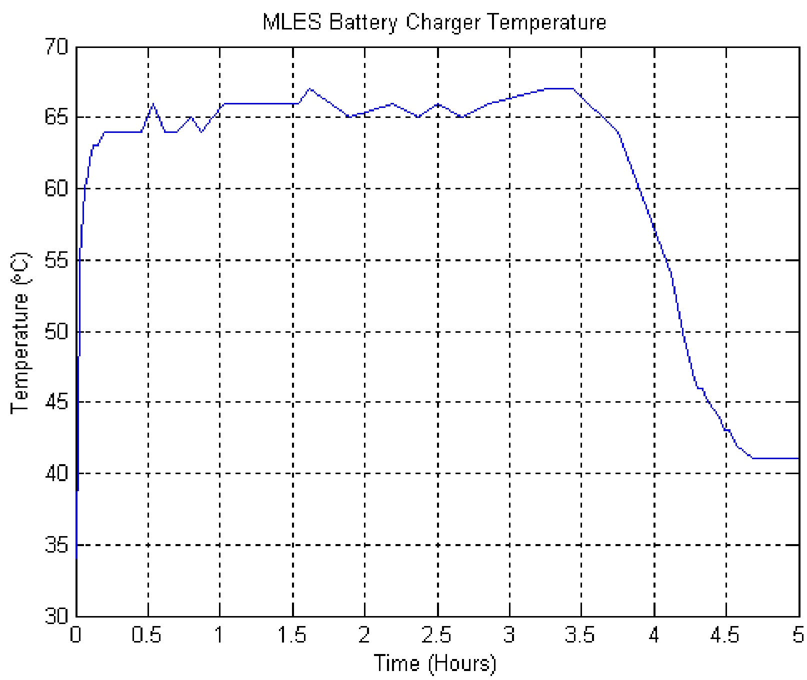

Figure 7.7: Temperature of the Battery Charger During Charge Cycle

7.3 Battery Life

It is important that the battery life of the MLES transmitter is long enough to support a full day of unmanned vehicle operation. Figure 7.8 shows the discharge curve of the Multi-Level Emergency Stop transmitter while operating in long range mode. As seen on the discharge curve, the battery life of the system is about 30 hours. This is more than enough to support a full day of operation. When operating in long range mode as opposed to low latency mode, data is transmitted 1/4 as often, increasing battery life. As a result, the expected battery life of the transmitter when operating in low latency mode is around 7.5 hours.

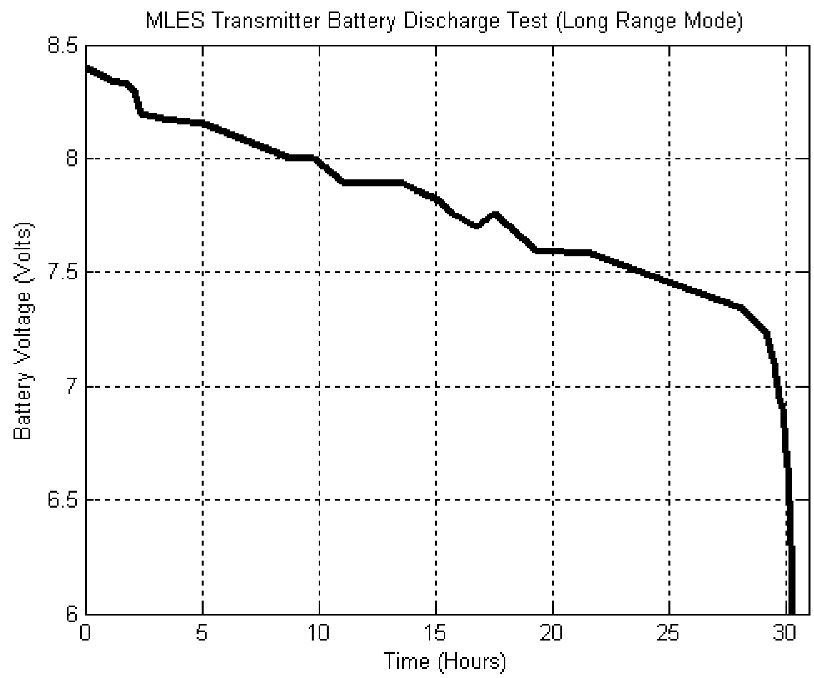

Figure 7.8: Battery Discharge Curve of MLES Transmitter (Long Range Mode)

7.4 Latency

The latency, or response time, of the MLES system is defined as the time from the actuation of a switch on the transmitter to the actuation of the relay contact. The actually response time can vary according to integrity of the wireless link. The ideal latency can be calculated assuming an ideal wireless link.

Data is transmitted and processed periodically with the same frequency on both the transmitter and receiver. The period of this operation is 71ms for low latency mode and 284ms for long range mode. Neglecting transmission time, the worst case response time can be calculated as the time it takes to execute two periods.

If a switch was actuated immediately after the current execution cycle checked the status, the actual position of the switch would not be read until one full cycle later. Once the actual switch position is sent, one instruction later, a similar situation can occur on the receiver. The receiving can then take up to one full cycle time to actuate the corresponding relay. This results in a maximum delay of 568ms and 142ms for long range mode and low latency mode respectively.

To verify this, a sample of 100 actuations was taken and measured using two channels of an oscilloscope with the transmitter and receiver in close proximity to one another. The median execution times was measured at 200ms for long range mode, and 100ms for low latency mode.

7.5 Range

It is important that range testing of the Multi-Level Emergency Stop system was performed to confirm that the design goals were met. Range tests of both the long range operation mode and the low latency operation mode were performed with two separate antenna configurations.

With a permanently mounted antenna on the transmitter, only the receiver antenna was changed during the range tests. The two antenna used during the range tests on the transmitter were a dipole antenna, and a high gain 5dBd antenna. The gain of the antenna is a measure of the amount of focus that an antenna can apply to an incoming signal. The dBd gain rating refers to the antenna gain with respect to a dipole antenna, in which case the dipole antenna would have a rating of 0dBd.

The range tests performed measure the received signal strength of the radio modems at various distances. The signal strength outputs are a measurement of the power of each packet that is received by the modem. These measurements are in dBm, or the measured power referenced to 1mW [4].

Figure 7.9 shows the results of the range test in the long range operation mode. In this mode, the receiver has a maximum sensitivity of -110dBm. Anything measured above -35dBm is considered full strength, resulting in a measurement range of -35dBm to -110dBm. Ideally these tests would reflect a true line of sight (LOS) measurements, but this was difficult to achieve at longer ranges. The tests performed were at ranges up to 1700 meters. During these tests LOS communications were lost in the range of 1000m to 1400m as well as all ranges above 1550m. The non-LOS distances are represented by the shaded blue regions in figures 7.9 and 7.10.

Represented in Figure 7.9 is the signal strength of packets received by the transmitter. There is a significant drop in the received signal strength around 1000 meters. This can be explained by the loss of line of sight communications from 1000m to 1400m. As expected, the dB measurement has a fairly linear relation to the distance. When comparing the results of the two different antennas, there

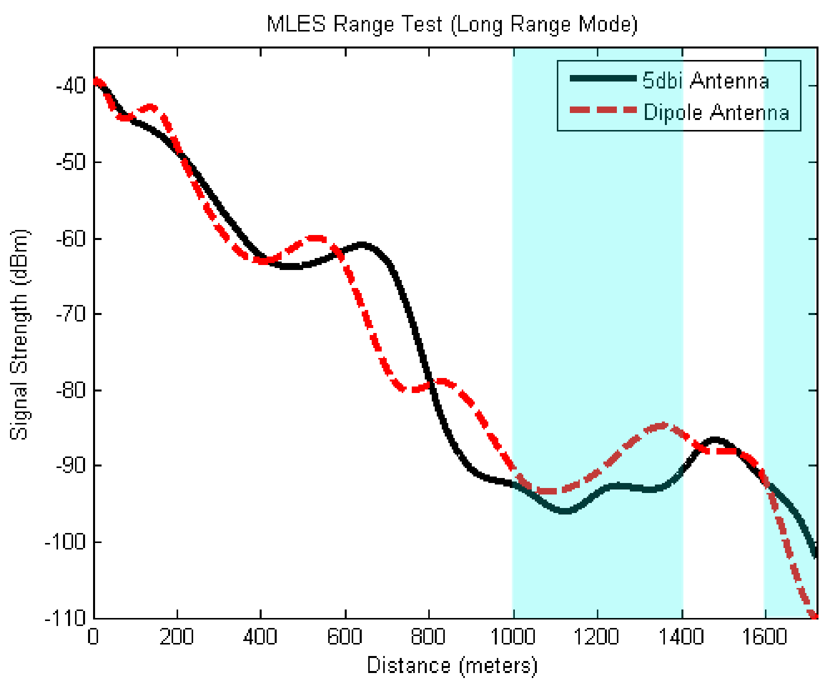

Figure 7.9: Range Test of MLES in Long Range Mode

showed little difference in the range performance. With the dipole antenna on the receiver, the range tests showed a maximum operating distance of 1700m before the signal was lost. With the higher gain antenna, there was a signal for the entire range test. However, the test only showed improved signal strength at the longer ranges. Only at ranges greater than 1400m did the performance of the system with the high gain antenna exceed that of the dipole configuration.

An identical range test was performed with the Multi-Level Emergency Stop system operating in low latency mode. The results of this test can be seen in Figure 7.10. In low latency operation, the maximum receiver sensitivity is changed from -110dBm to -100dBm. The results of the low latency test are similar to those of the long range operation. During the non-LOS distances, the signal was lost with the dipole antenna. This is not surprising since the receive signal strength was around -100dBm in the long range tests at the same distance. The maximum range of the system in low latency mode was around 1600 meters, which was expected due to the decrease in receiver sensitivity. The rapid drop off in measured sensitivity toward the upper distances can be attributed again to the loss of line of sight communications.

While the range tests offer the maximum operating distance of the Muti-Level Emergency Stop system, there is a lot of uncertainty and variability in these tests. The signal strength measurements are a measure of the signal strength of an incoming packet, not necessarily a valid incoming packet. The signal strength measurements are also affected by many factors such as antenna placement and orientation. What can be observed from these tests is the operating range of the system.

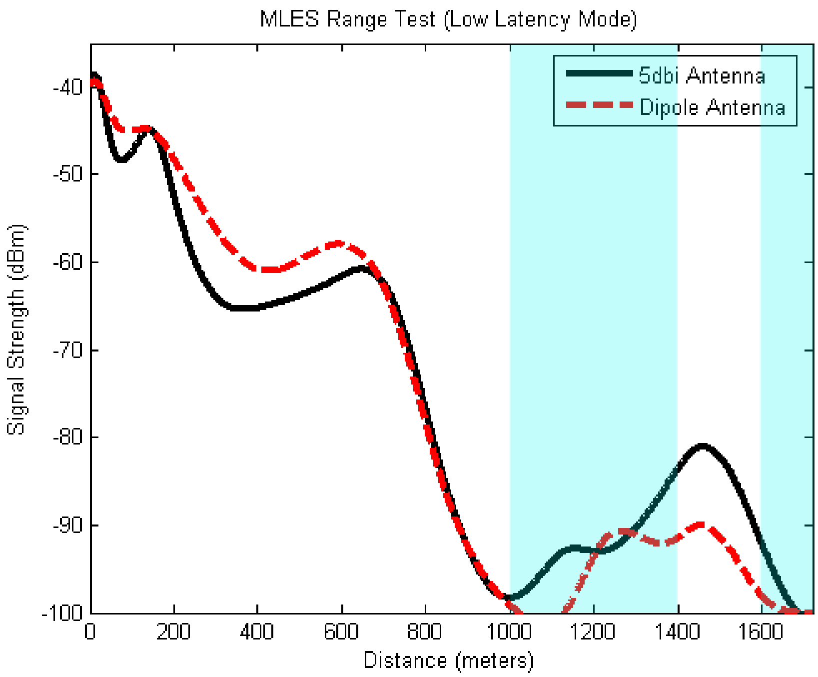

Figure 7.10: Range Test of MLES in Low Latency Mode

In order for the MLES system to be operational, the transmitter (or receiver) must receive a valid packet within a certain amount of time from the last valid packet that was received. In particular, this is set to 20 cycles in software, or 5.4s in long range mode, or 1.4s in low latency mode.

7.6 Error Rate

To gain a better understanding of the performance of the Multi-Level Emergency Stop system, the percentage of valid packets with respect to signal strength was tested. From this data, an understanding of the response time of the MLES system can be obtained at different signal strengths. The results of these tests can be seen in Figure 7.11. The results of this test show the percentage of packet errors received over 10000 total packets at various signal strengths.

As seen in Figure 7.11, packet errors become a significant factor when dealing with signal strengths less than -80dBm, and there were no packet errors seen at signal signal strengths greater than -70dBm. Factoring this data in with the latency, we can expect that the ideal latency calculations will hold for signal strength readings above -70dBm. Measurements less than -70dBm can start to see dropped packets and effect the latency of the system.

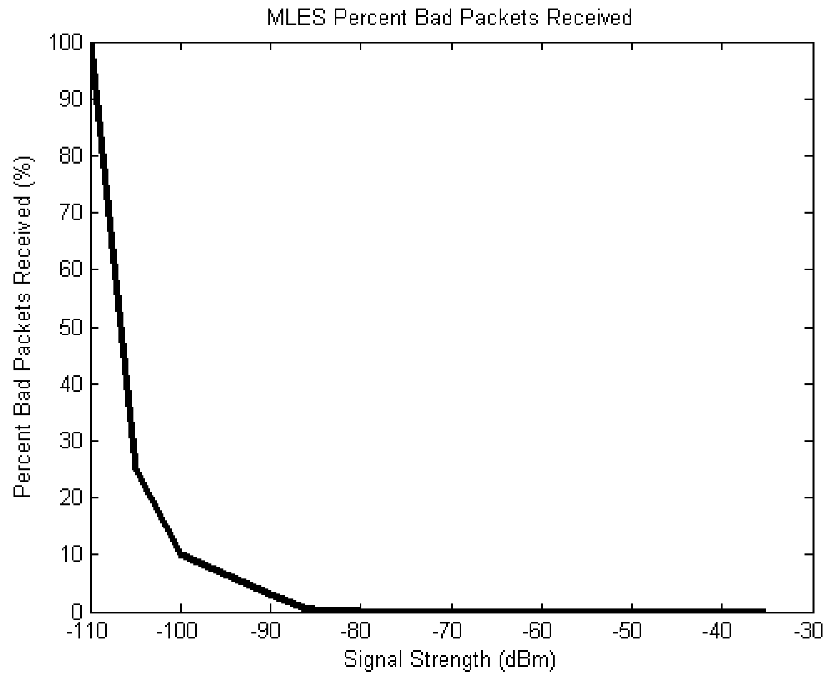

Figure 7.11: Percent Error Rate

Table 7.1: MLES Cost Breakdown

	Receiver	Transmitter	System
Electronics	$298.00	$281.00	$579.00
Hardware	$37.00	$290.00	$327.00
Enclosure	$50.00	$89.00	$139.00
Total	$385.00	$660.00	$1,045.00

7.7 Cost

With a parts cost of just over $1050, the Multi-Level Emergency System exceeded the initial cost estimate of $1000. As seen in Table 7.1, the electronics make up only a fraction of the total system cost. A major portion of the total system cost is in the hardware. This includes the connectors, switches, joystick, antennas, and battery of the MLES. Although cheaper alternatives existed, the components selected for the Multi-Level Emergency Stop were chosen with reliability as the primary factor.

Chapter 8

Conclusions

Through the many revisions over the past two years, the Multi-Level Emergency Stop system has evolved into a refined finished product. There have been previous versions of the MLES in use for the past year, proven to provide reliable operation. The many revisions have been redesigned to ensure that the majority of the initial design goals have been satisfied.

In many cases, the performance of the Multi-Level Emergency Stop system exceeded the initial design specifications. The operating range of the system was shown to operate at over a mile without direct line of sight communications. Considering that non-LOS communications drastically reduces the operating range, this is a considerable improvement over initial design goals. With the incorporation of two operating modes, the MLES can last for around 30 hours on a single charge, which well exceeds the design criteria.

The improved battery life and operating range do have some disadvantages.

Due to the improved antenna and battery on the transmitter, the weight is slightly greater than initially designed. The added capabilities also have added to the total cost to the system. The total parts cost for assembly is slightly greater than the original goal of $1000.

Perhaps the most important test on the MLES system is the reliability. There have been versions of the Multi-Level Emergency Stop system in use for over a year without incident. Though the development history, the Multi-Level Emergency Stop system has been an effective safety measure for a variety of unmanned vehicles.

8.1 Future Work

With a reliable hardware platform there are no hardware modifications needed on the Multi-Level Emergency Stop system. The firmware running on system has also provided reliable operation. Having been through several revisions, the enclosures of the Multi-Level Emergency Stop system provide a rugged weather resistant housing while providing the professional look of a finished product.

With the many user configurable options, the command mode of the Multi-Level Emergency Stop can be overwhelming. For this reason, a graphical user interface would simplify the configuration of the system. Although there was never a graphical interface planned during the development of the MLES, the command mode was implemented in such a way that a graphical user interface could easily be implemented. Serving as a graphical overlay to the command mode, a user application for the Multi-Level Emergency Stop system could easily keep track of individual vehicle settings and configure the Multi-Level Emergency Stop system.

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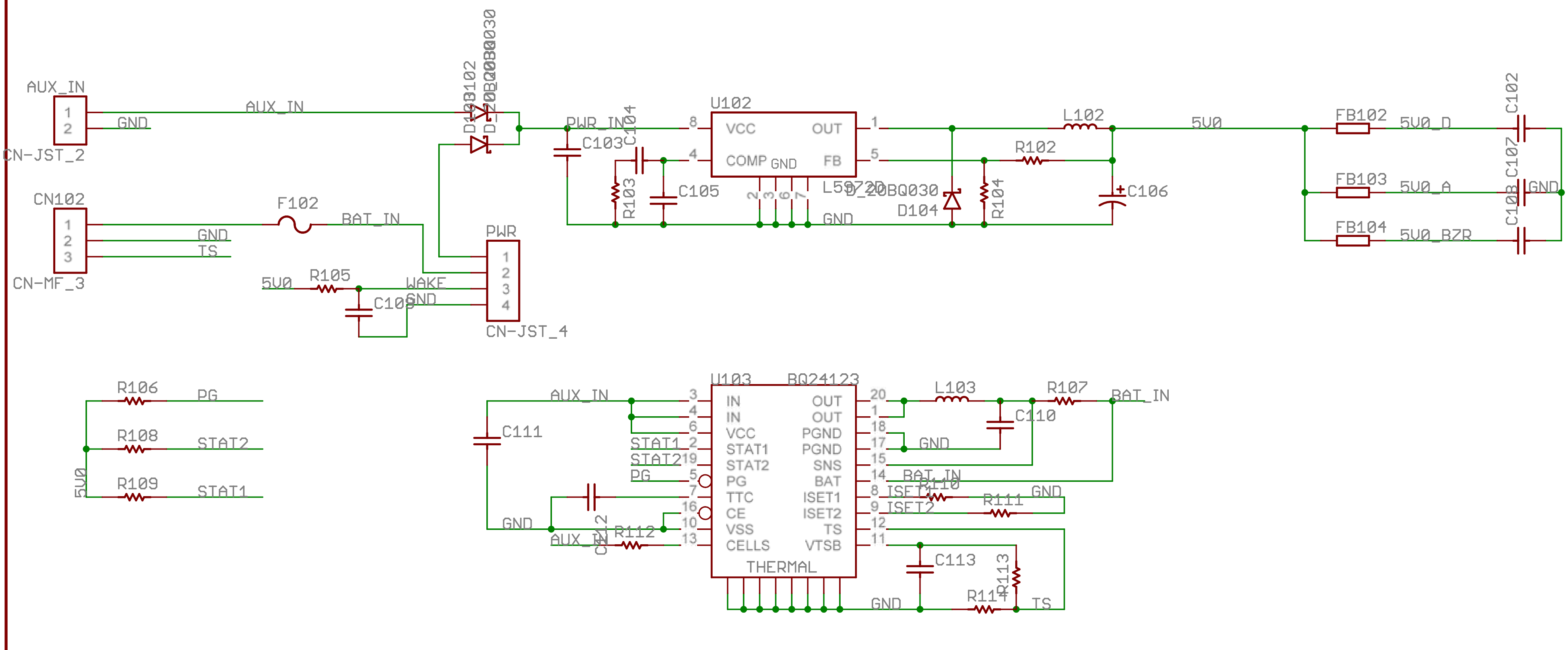
Appendix A

Schematics

Schematics of the Multi-Level Emergency Stop System.



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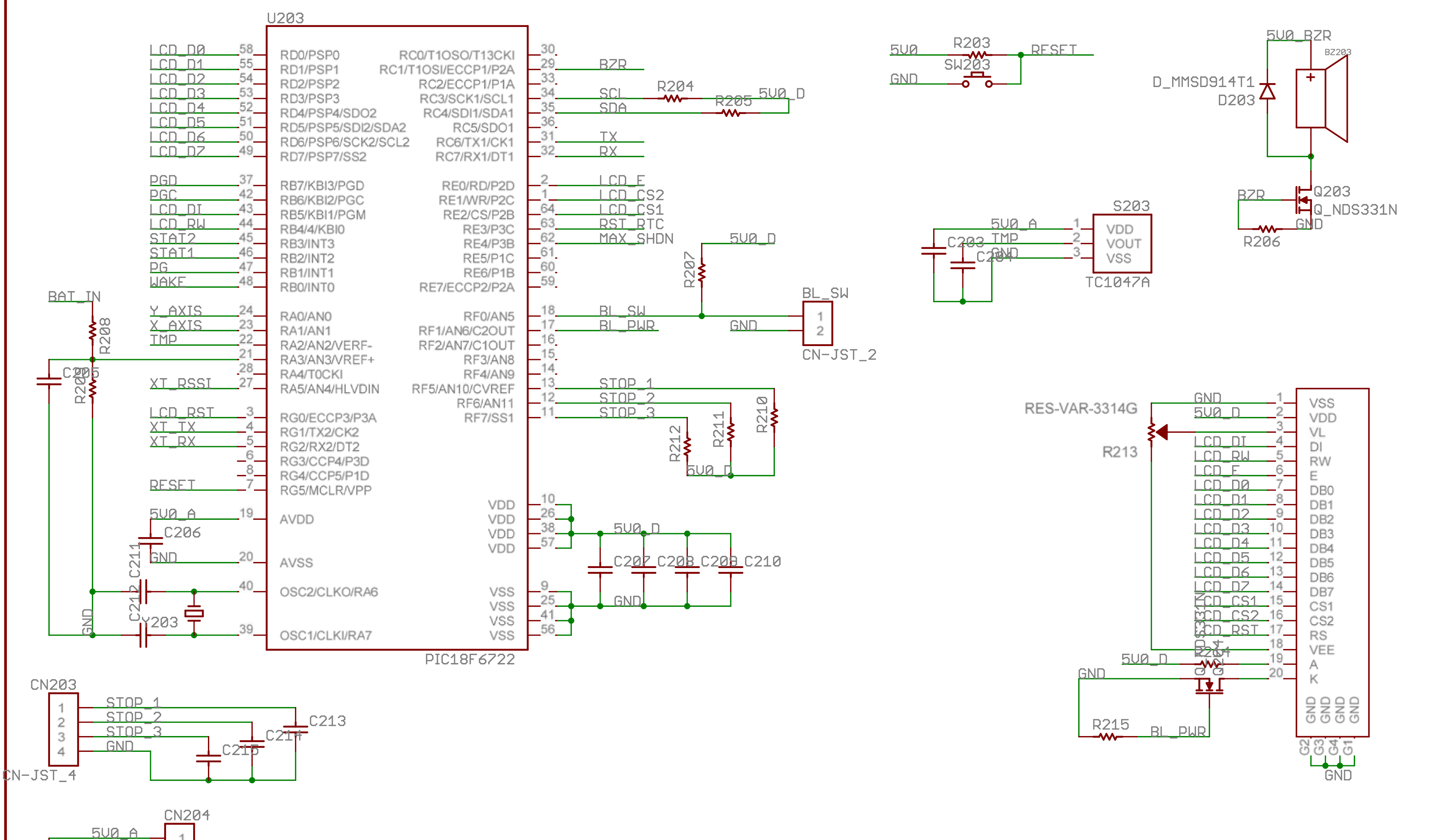

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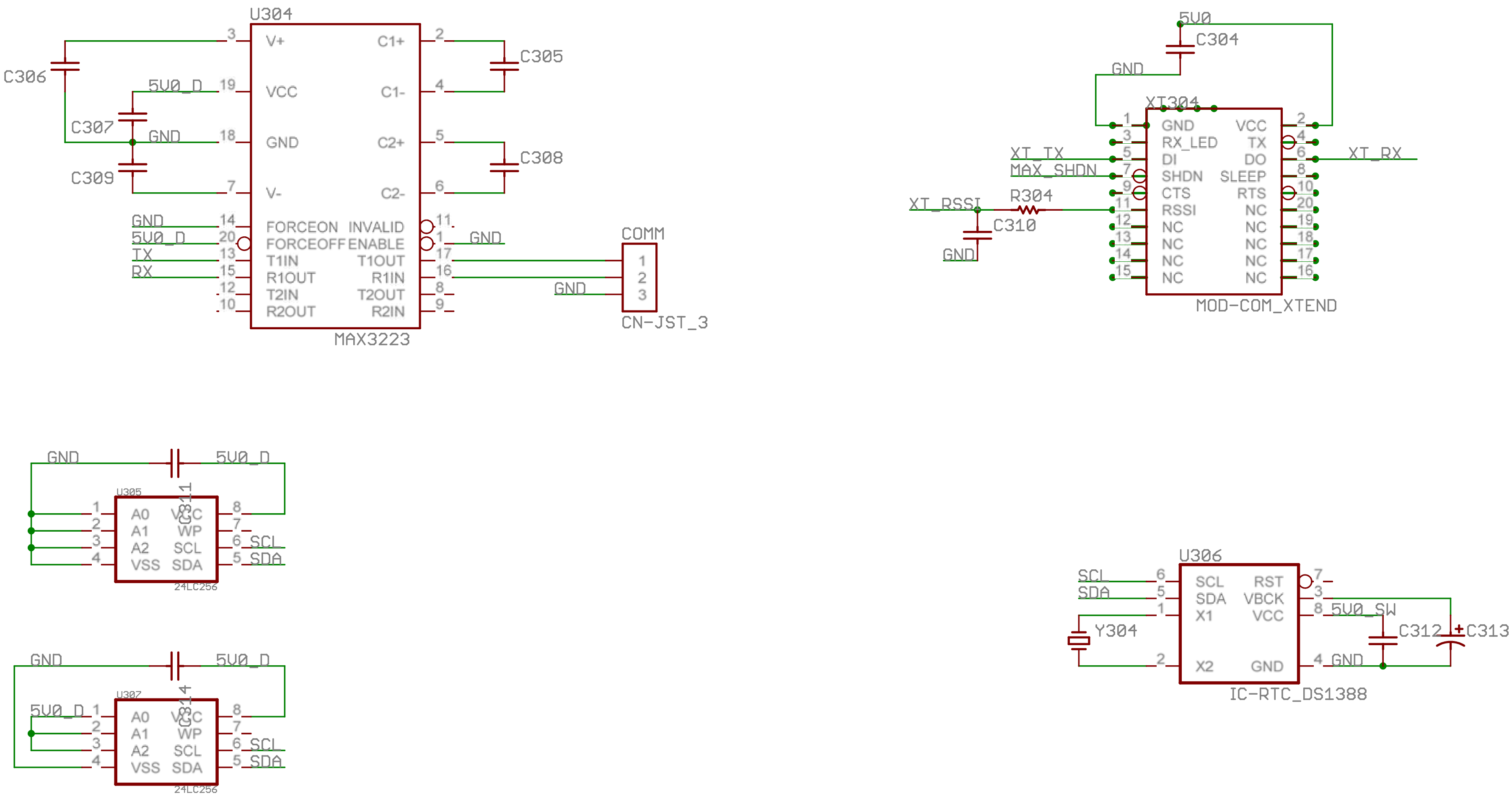

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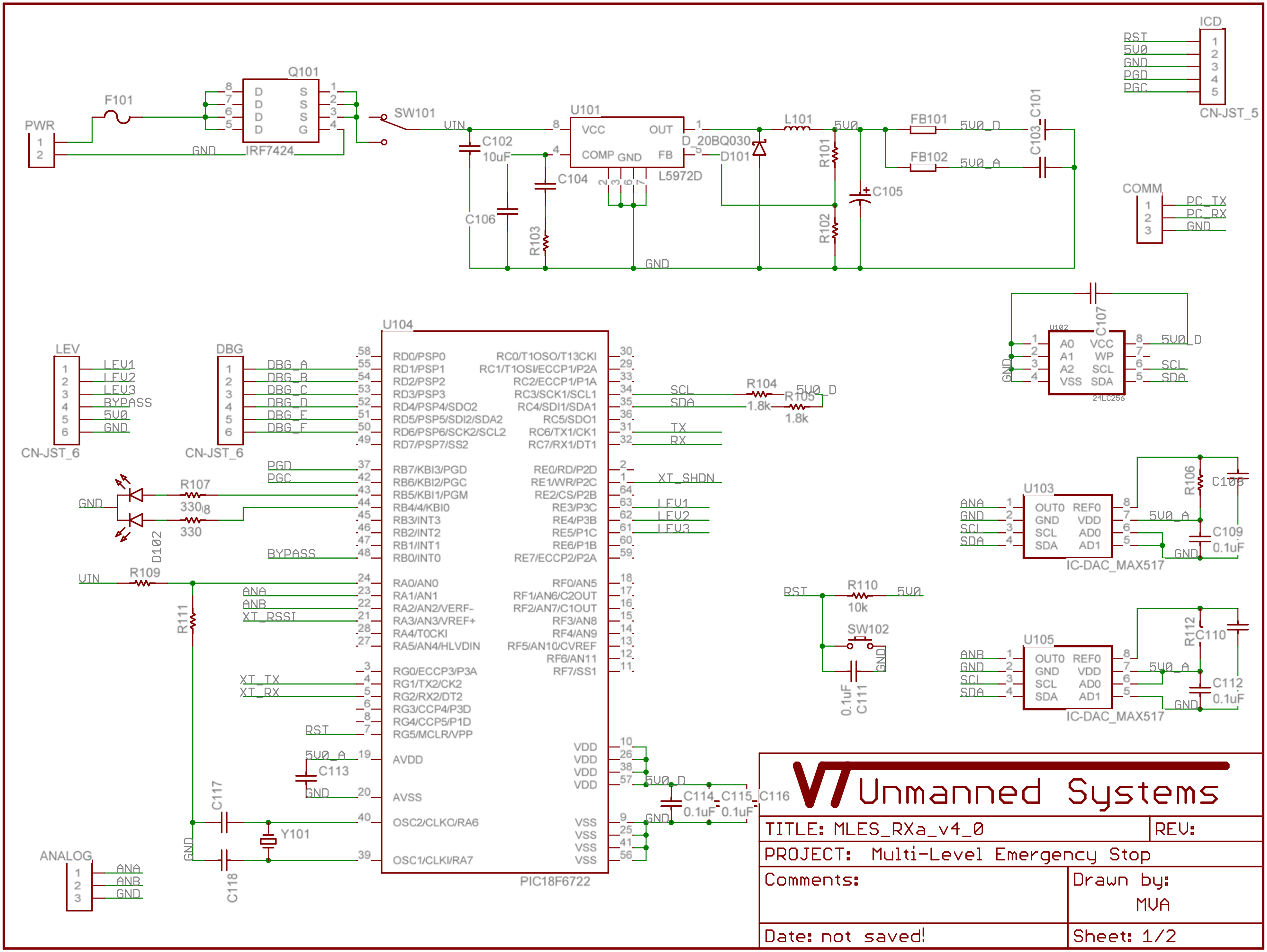
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C103
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RX
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R108 330
D102
R109
R111
ANA
ANB
XT_RSSI
XT_TX
XT_RX
C113
C117
C118
Y101
ANALOG
U103
U105
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C108
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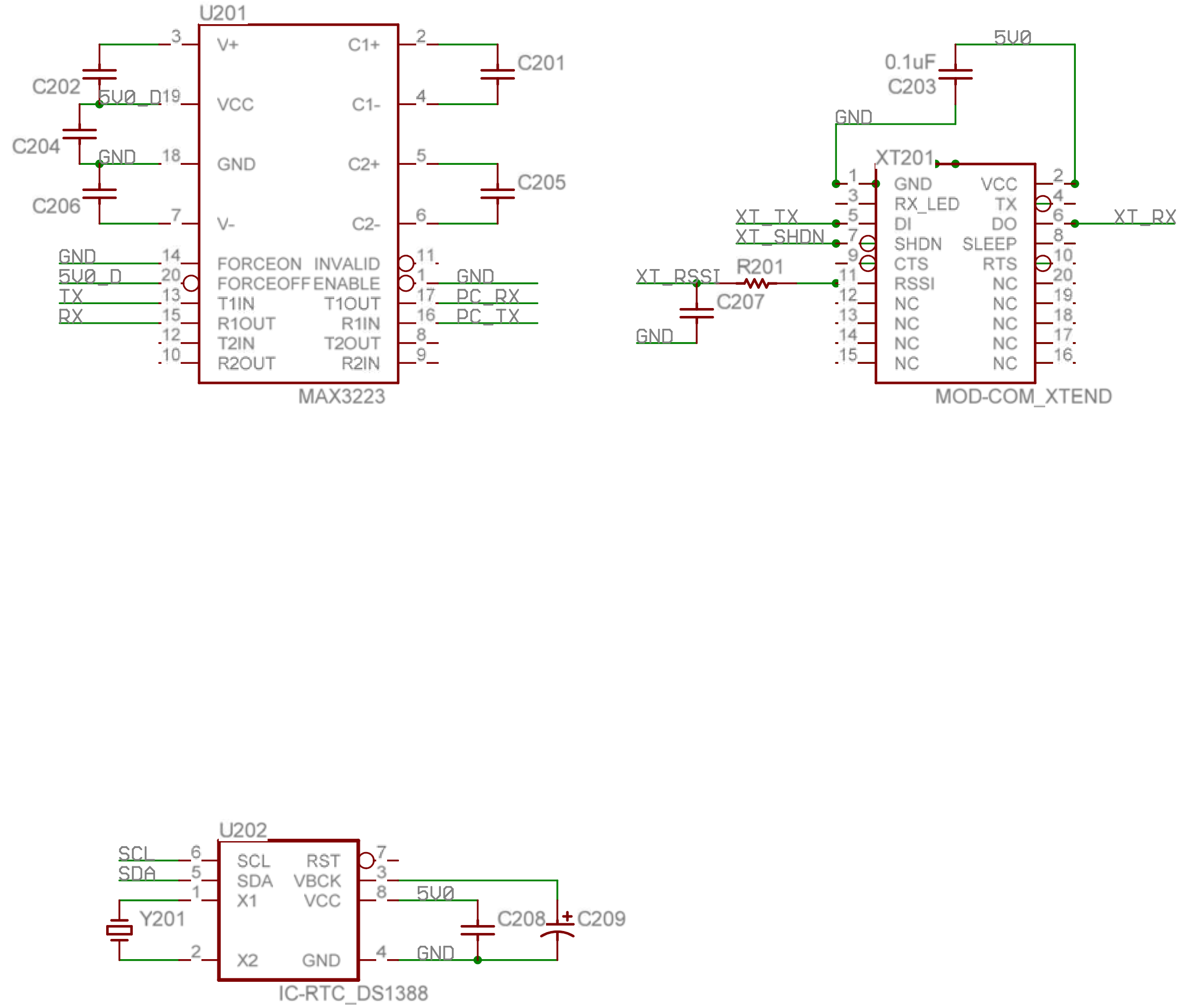

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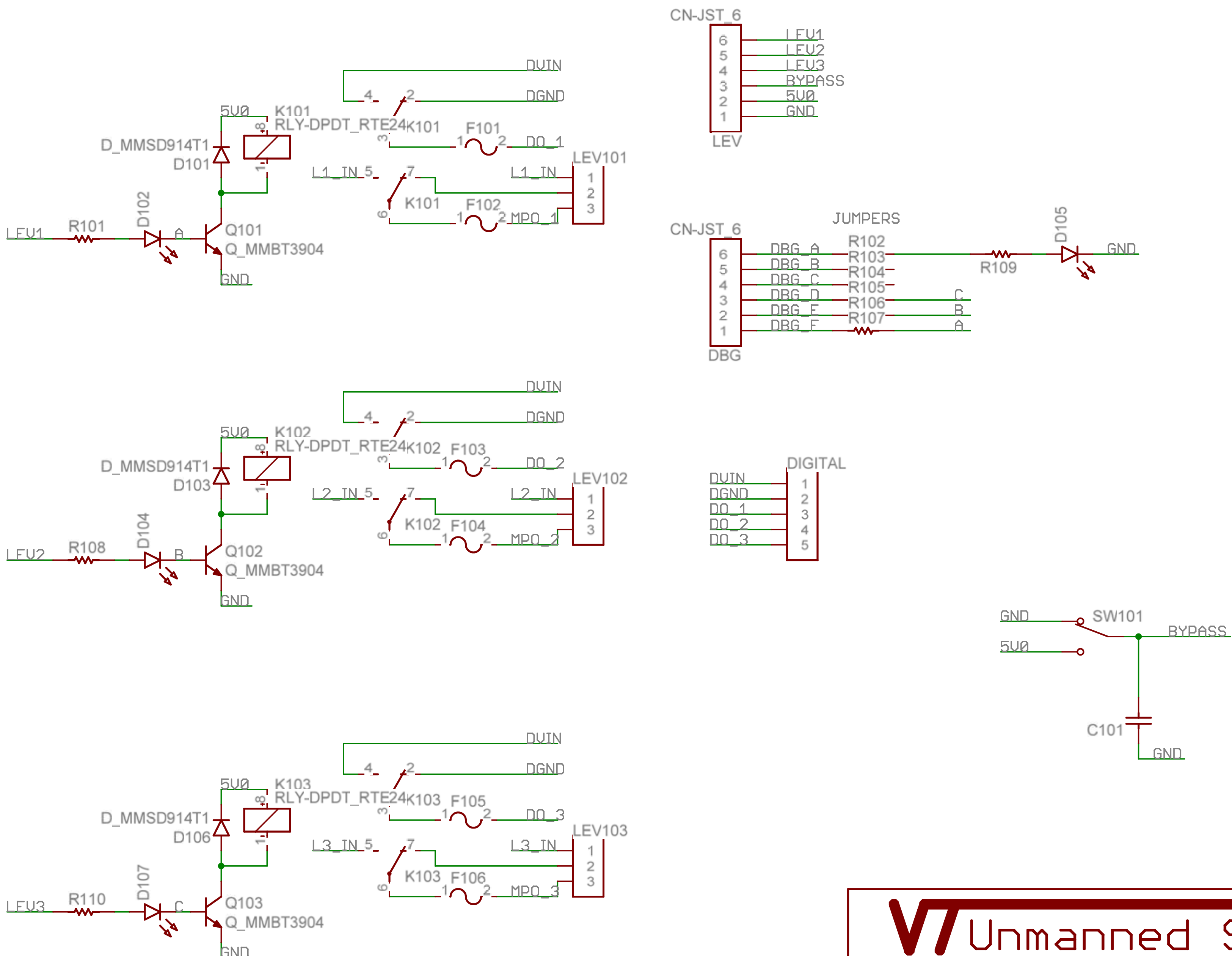

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