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## ABSTRACT

This senior project involves the complete system design and construction of a "Nerf" sentry gun to replace an armed guard. We aimed to develop a compact and highly mobile defense system that allows operational flexibility. The sentry gun can autonomously track and shoot at moving targets, while also allowing a user to remotely access and control the gun via computer. The mobility, hardiness, and functionality of this system allows a reliable replacement for human beings in harsh and hostile environments; ultimately sparing a life.

## I. INTRODUCTION

The initial idea for this project came from a military based video game where a player could put down a “sentry gun” and it would then automatically target, track and shoot at enemy players without the player having to supervise the system [1]. To my knowledge, this system does not readily used by the military even though it has great potential. It parallels the purpose of the MQ-1 Predator made by General Atomics; an UAV used in military applications. The system would replace the active functions of an armed guard while keeping a human life out of harm’s way. Since this system would replace a human, we wanted to make it as accessible as possible which lead to idea of having the system remotely accessible and piloted by a user. To allow the user to have as much information about the place the system operates in, we wanted to add several environmental sensors can also log system location and weather conditions. This remote accessible data could allow for military planning for that environment. Overall, we this system has a lot of potential in modern day military strategy and would help spare hundreds of our ally’s lives.

Several other sentry gun projects exist. Websites including *RealSentyGun.com* and *ProjectSentryGun.com*, contain full system overviews of the sentry guns that they have built [2][3]. Their systems appear extremely similar to our system, but vary due to the fact our system uses a Nerf gun instead of paintball guns, out system features environmental sensors and remote (long distance) computer piloting. The Australian Navy currently utilizes the sentry gun system “Gladiator II,” sold by *RealSentryGun.com,* to help train their soldiers [4]. We hope, like the Gladiator II, that our system becomes a useful entity for military application, and forwards the use of robot technology in modern military strategy.

## II. SPECIFICATIONS AND REQUIREMENTS

TABLE I

AUTONOMOUS/REMOTE PILOT SENTRY GUN REQUIREMENTS AND SPECIFICATIONS [5][6]

| Marketing Requirements | Engineering Specifications | Justification |
|---|---|---|
| 7 | System cannot exceed the *weight* of 40 lbs. and must not exceed the *dimensions* of 3’ x 3’ x 6’, when setup in a static position. | The system must allow high mobility. The average trained technician should have the ability to carry the turret. When system becomes portable, it must fit in a vehicle or specialized case. |
| 1, 6 | Turret should *communicate,* with minimal data loss and a high data rate, with a remote controlling computer for user control. To provide communication to the system, the use of a commercial internet broadband service should ensure a wide operating area, for a low price. | The system needs to send and receive data with minimal latency to give the user the most accurate situational data. With any time delays, a target may change positions by the time the user in the remote location receives the old positional information. |
| 8 | Communication security keeps *unauthorized users* (personnel of neither ally nor remote user relation) from interfering with the system. | System targeting sensitive to friendly and enemy targets, the system should not allow unauthorized users to access the targeting and triggering system. |
| 1, 2 | When the *system setup occurs* in an environment, it must perform software/hardware setup and diagnostics to ensure proper operation, along with calibration to objects, lighting and weather conditions in the environment to allow for easier targeting of foreign objects. | Every time the system turns on, it must check to make sure that all of its features work correctly, and then relay the results to user. Environmental calibration allows the system to detect foreign objects that may enter the environment which may resemble enemy targets. |
| 3, 7 | System must run solely off of an *on-board power source* for a minimum of 6 hours in *sleep mode* and a minimum of an hour in *active mode*. *Sleep mode* describes the system state when in a low power state and not actively tracking targets. When in *Active Mode* the gun actively tries to find targets, and track and shoot them which ultimately uses more power. | This system must operate in remote locations where power sources possibly don’t exist. The system may reside in a location and left alone (except though remote access). The long battery life works in conjunction with the low power operation of *sleep mode*. When in *Active Mode* the system uses a more power due to more complex computation for tracking and servo powered gun movement. |
| 1, 2, 6 | The system’s “Autonomous Mode,” must *accurately identify* the enemy targets, which don’t have ally tags, and *track* them visually and physically with the pan/tilt system, regardless of light conditions. Target identification requires a minimum 98% success rate. | “Autonomous Mode” requires no human control, along with no human judgment on identification of a target. The system must identify who or what meet target requirements on its own, then track the target. Since targets may appear during the day or night, the system must accurately detect targets consistently in a changing environment. To the system, targets resemble humans, often moving and not wearing a “friendly ID tag” on them. |

| | | |
|---|---|---|
| 1, 2, 6, 7 | The system's "Remote User Mode," must allow a user to have a simple interfacing program on their computer, to allow control of the turret. | The remote user must simply control the turret via a computer program, allowing full functionality of the turret. The program must provide streaming video from the turret, allow the pan and tilt of the turret for surveillance and targeting, and allow turret triggering for eliminating targets. |
| 1 | The system must have a large *Field of view*. The turret must pan at least 180º and tilt at least 90 º to meet the minimum field of view requirements. | Since the system operates in one spot, it must pan and tilt to detect targets in the set location and to track the targets as they move through the area. |
| 9 | The system must monitor environmental data such as temperature, location coordinates, humidity and light conditions. | Since the system may reside in remote locations, the system should log the environmental conditions to provide statistical data to the users, either live via remote user mode, or from on board system storage. This allows the user to understand what to expect if they plan to go to the location of the system. |
| 4, 5 | System must handle diverse environmental conditions including temperatures (-10 º C to 60 ºC) and all degrees of humidity (0% to rain). Described as NEMA Enclose Type 3 [7]. | This system may reside in remote locations, without restrictions to hot or cold weather. The system's electronics must have protection against humidity or rain, to optimize usability. |

**Marketing Requirements**

1. Accurate targeting.
2. Function during day and night.
3. Power efficient.
4. Highly weather resistant.
5. Durable system housing.
6. Easy to operate.
7. Portable.
8. Secure.
9. Provide environmental interface.

This Table comes from a template in R. Ford and C. Coulston's *Design for Electrical and Computer Engineers* textbook [5].

The sentry gun system identifies human targets and tracks, and then shoots at them with Nerf darts to "eliminate" the target. The sentry gun's high portability and resistant housing allows for ease of use and does not limit it to certain environments. With ease of use as a main focus, the system allows autonomous operation along with easy switching to remote pilot mode. Autonomous mode eliminates the need of an on-sight operator while the remote pilot mode allows a remote user to access system data, environmental statistics and control the system via computer. Since the system allows remote controlling via internet, a secure communication between the system and the remote computer requires attention; so no unauthorized users can take control over the system. Since the system has the option to deploy remotely, with the possibility of no allies present, it requires long operation life which depends on the on-board power source capacity and efficiency of hardware and software. The gun identifies human targets and tracks them as they move in front of the device. "Ally" humans become avoidable by wearing identification tag which "enemy" targets do not have. The view of field of view of the system allows targeting and tracking over a large area via large system pan and tilt angles (at least 180º for pan and at least 90º for tilt). An array of environmental sensors (described above) provide remote users real-time environmental conditions, to give the user a more complete understanding of the location the system resides in, while allowing traceable data for future planning for tasks in that environment.

## III. DESIGN DECOMPOSITION

### Level 0 System Block Diagram

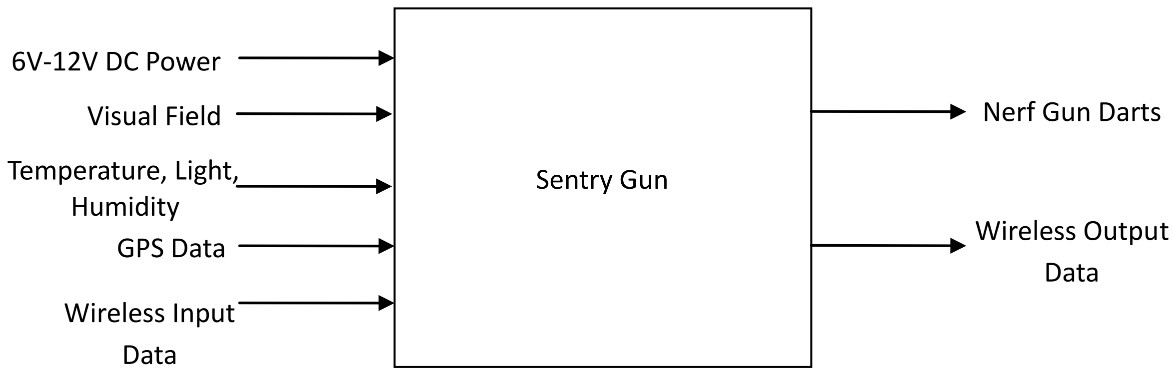


Figure 1. Level 0 Sentry Gun System Block Diagram.

TABLE II
TOP LEVEL INPUTS, OUTPUTS AND THEIR FUNCTIONALITY
(Refer to visual representation above in *Figure 1*)

| | |
|---|---|
| *Module* | Autonomous/Remote Pilot Sentry Gun |
| *Inputs* | - DC Power: 6V- 12V<br><br>- Visual Field: Field of view that an onboard camera can see. Since funding dictates camera resolution and quality, the camera for the system may change; yet the minimum quality should allow the on-board computer to still preform target recognition and tracking.<br><br>- Environmental Conditions: The system logs temperature, light and humidity statistics for use by users for environmental understanding and future planning.<br><br>- GPS Data: Data sent to the system from GPS Satellite which establishes system location.<br><br>- Wireless Input Data: Incoming wireless data contains pan/tilt controls, firing commands, and remote system wake-up from remote computer. The system uses cellular broadband as the communication network. This allows system placement in range of anywhere where cell phone towers reside. |
| *Outputs* | - Nerf Gun Darts: The gun shoots at targets using Nerf darts.<br><br>- Wireless Output Data: Outgoing real-time video and system status updates to the remote controlling computer. |

| | |
|---|---|
| *Functionality* | The sentry gun uses a camera to see targets and then proceeds to shoot Nerf darts at them. In "Remote User Mode," the system outputs real-time stream the video to the remote user's computer via wireless internet, while the remote user can control the sentry gun system using commands. |

This system has several inputs and outputs (refer to *Figure 1)*. The system requires DC power to power the system as a whole, with the voltage ranges allowing multiple possible power sources. The field of view encompasses the environment that the system can view and all the objects within it, when using a camera. The Wi-Fi signal transfers data between the system and remote computer to allow remote piloting and environmental data viewing. The gun's only output's the Wi-Fi data stated previously and the Nerf darts used to shoot/"eliminate" targets.

## Level 1 System Block Diagram

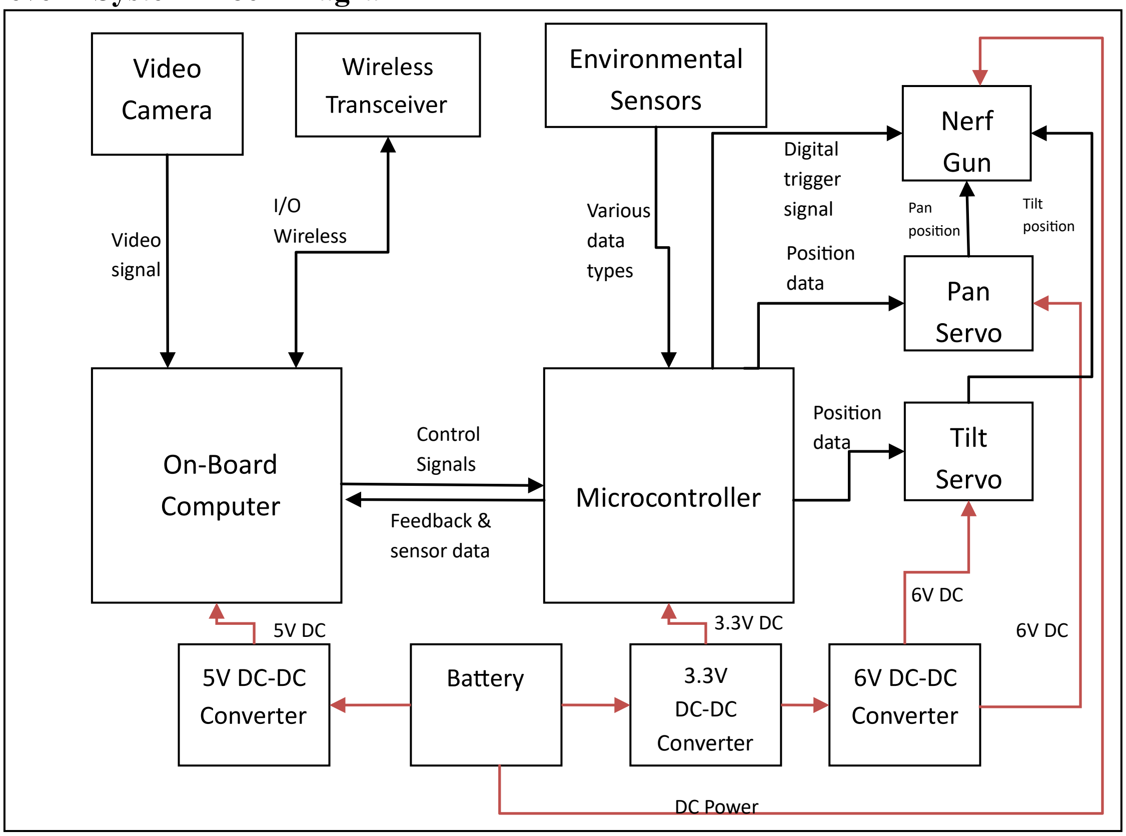


Figure 2. Level 1 Sentry Gun System Block Diagram.

TABLE III

LEVEL 1 SUB-SYSTEMS' BREAKDOWN

(Refer to visual representation above in *Figure 2*)

| *Module* | *Inputs* | *Outputs* | *Functionality* |
|---|---|---|---|
| Battery<br><br>(Voltage TBD) | Electricity from charger | $V_{DC} > 6V$ | Provides DC power to the whole system |
| 5V DC-DC Converter | $V_{DC}$ from battery | 5 $V_{DC}$ | Provides 5$V_{DC}$ required to power on-board computer |
| 3.3V DC-DC Converter | $V_{DC}$ from battery | 3.3 $V_{DC}$ | Provides 3.3$V_{DC}$ required to power microcontroller (operating at 3.3V saves battery power) |
| 6V DC-DC Converter | $V_{DC}$ from battery | 6 $V_{DC}$ | Provides 6$V_{DC}$ required to power pan and tilt servos |
| On-board computer<br><br>(Pandaboard) | • 5 $V_{DC}$<br>• Servo position Feedback and sensor data from microcontroller<br>• Data from wireless transceiver containing remote computer commands<br>• Video feed signal (type TBD) | • Control data for microcontroller<br>• data from wireless transceiver | Computer analyzes video for target identification, control microcontroller to have servos track target with gun, and handle commands and data transmission to/from remote computer |
| Microcontroller<br><br>(TBD) | • 3.3$V_{DC}$<br>• Commands from computer (servo positions and poling for sensor data)<br>• Data from environmental sensors | • Positional data for pan and tilt servos<br>• Trigger signal for shooting gun<br>• Data from environmental sensors to computer.<br>• Servo feed-back to computer | The microcontroller handles peripheral subsystems, as in, the sensors and servos because the computer cannot due I/O limitations (power, I/O types). This in-turn increases computer performance by splitting up the work load with the microcontroller. |
| Pan Servo | • 6$V_{DC}$<br>• Positional data from microcontroller | • Pan motion of gun of $\geq 180^{o}$ | Allows the gun to pan from side to side; for target tracking. |
| Tilt Servo | • 6$V_{DC}$<br>• Positional data from microcontroller | • Tilt motion of gun of $\geq 90^{o}$ | Allows the gun to tilt up and down; for target tracking. |
| Nerf Gun | • Digital Trigger signal from | • Nerf Darts | Shoots darts at targets |

| | | | |
|---|---|---|---|
| (Vulcan EBF-25) | Microcontroller<br>• Battery Power<br>• 3D movement from pan and tilt servos | | tracked by system. |
| Video Camera | $V_{DC}$ (voltage TBD) | Video feed signal to computer | The video camera sees the environment, which allows the computer to identify targets then track them. |
| Wireless transceiver | • Video feed, system and sensor data from on-board computer<br>• Commands data from remote computer | • Data to onboard computer<br>• Data to remote computer | Allows network communication between the on-board computer and the remote computer. This allows sensor data and video to send to remote computer and allows controls from remote computer to control system |

The level 1 system block diagram above in *Figure 2* and their functional breakdowns explained in *Table II* shows the required sub-systems for the system's functionality. The Pandaboard became the on-board computer of choice because of its small size, low power consumption, and processing power [8]. The on-board computer handles complex data input including remote computer commands via wireless transceiver and video feed which required frame-by-frame analysis. With this, it analyzes the video feed to identify and track targets in the system's field-ofview. Once the system identifies a target, the computer sends positional data to the microcontroller, and ultimately to the servos, to aim the gun at the target and updates the position accordingly to track the target as it moves. Also when target identification occurs, the computer sends a shoot command to the microcontroller to trigger the gun's shoot mechanism which shoots at the tracked target. In remote pilot mode, the video feed from the camera streams, real-time, to a remote computer via wireless communication where the user can then use a remote computer to send back manual aiming commands (via keyboard arrow keys) which the on-board computer then uses to control gun position and shooting. The environmental sensors provide environmental data for the given location the system resides in; this includes temperature, GPS location, humidity, and lighting conditions. The microcontroller samples this data and sends it to the on-board computer for statistical logging, and if in remote pilot mode, the system sends data to the remote computer for logging and display. The power circuits (DC-DC converters) provide each subsystem with their individual required operating voltage. These converters connect to the on-board battery which powers the whole system. A combination of efficient sub-systems and high amp-hour rated battery aids long operational life for the overall system.

## IV. WORK BREAKDOWN STRUCTURE

This project breaks down into several main system categories which contain work packages.

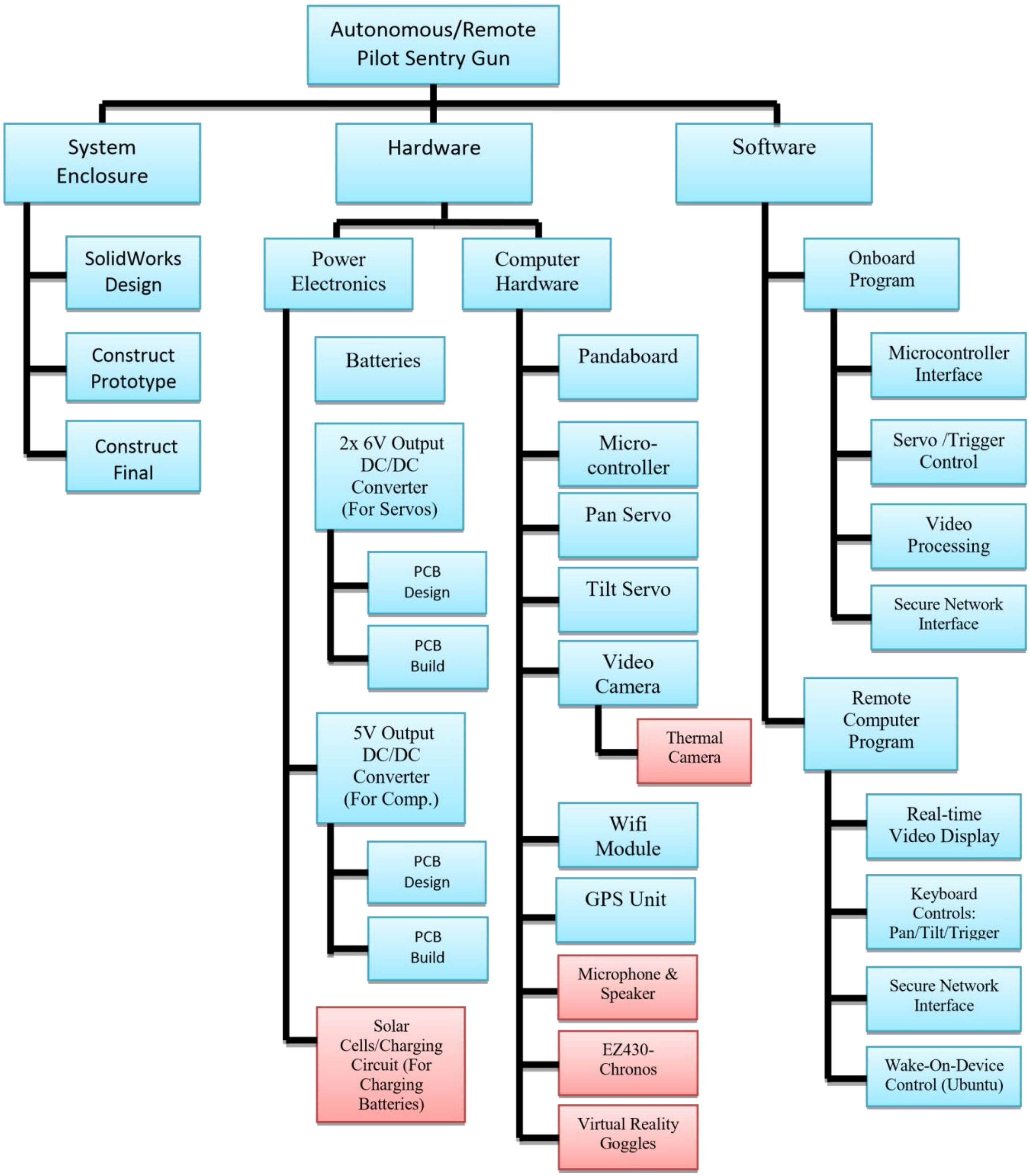


Figure 3. WBS and sub-systems required to complete the sentry gun project. The blue work packages represent the required work for the system. Red work packages represent the possible system additions given extra time and resources.

## V. INITIAL GANTT CHARTS

Figure 4. Gantt Charts showing the estimated work breakdown structure of the sentry gun project. Gantt chart incorporates estimated time for part shipments.

The Gantt chart in *Figure 4* starts at current day in EE460 (winter quarter), continues through EE463 (spring quarter) then the remainder continues in EE464 (fall quarter). As of now I am mainly in charge of hardware design and implementation for the system where Dante mainly handles software design and implementation. Since the number of group members may vary, dates may vary based on the ability for our group to work on work packages in parallel. Continuous documentation occurs as the project progresses to make the final report more accurate and less tedious.

The pan/tilt servos and the Nerf gun I already own, thus a fixed cost for those parts. The broadband USB stick requires monthly service fees for operation which may vary when we purchase the component.

As of now the cost estimates come from major sub-system average prices for the overall system. Due to uncertainty, manufacturing costs and possible revision costs proved uncertain at this stage in planning.

## VII. ELECTRICAL SYSTEMS

With a scope for the project developed and goals reasonably planned, the design process for each of the individual subsystems began to take place. These subsystems were then split into three major sections: electrical, mechanical and software.

Looking at the scope of the electrical systems, there are varies requirements for basic functionality. The Pandaboard computer is required for running the main system program, analyzing camera feed and handling networking functionality for remote computer access. The microcontroller shield, named “Kung Fu Shield” for hilarity purposes (“Kung Fu Panda”), is required for pan and tilt servo actuation, system power management and sensor acquisition. The rest of the system is comprised of infrastructure wiring and circuitry which is used to interconnect the electrical systems throughout the sentry turret.

### A. *Kung Fu Shield (Microcontroller Board)*

Before actual design for the Kung Fu Shield could take place, the specific functionalities required for the board design needed to be finalized.

ELECTRICAL REQUIREMENTS:

*Power Management*

- Provide 5V power to run the Pandaboard
- Provide 3.3V power for Microcontroller board logic, peripheral devices and sensors
- Provide 6V power for large pan and tilt servos
- Input power protection for both microcontroller and Pandaboard.

*Mechanical Actuation:*

- PWM output for pan and tilt servo position control

*Communications:*

- Pandaboard communications
- Hardware access to UART, SPI and I2C communication protocols
- LCD screen for display and debugging

*Sensor Acquisition:*

- Battery voltage monitoring
- System current consumption monitoring
- Hardware temperature monitoring
- Environmental Temperature and Humidity
- GPS

Another important design requirement involved the physical size and placement of the Kung Fu Shield. Since this board acts as an extension of the Pandaboard, the Kung Fu Shield was to attach directly on top of the Pandaboard. The Pandaboard has an array of general I/O pins which allow access to various power and communication hardware that the Pandaboard offers. Referring to *Figure 5*, The "Expansion Connector" on the Pandaboard is where the Kung Fu Shield was designed to be connected. Through the Expansion Connector the Kung Fu Shield will be providing 5V power to the Pandaboard and communicating via UART.

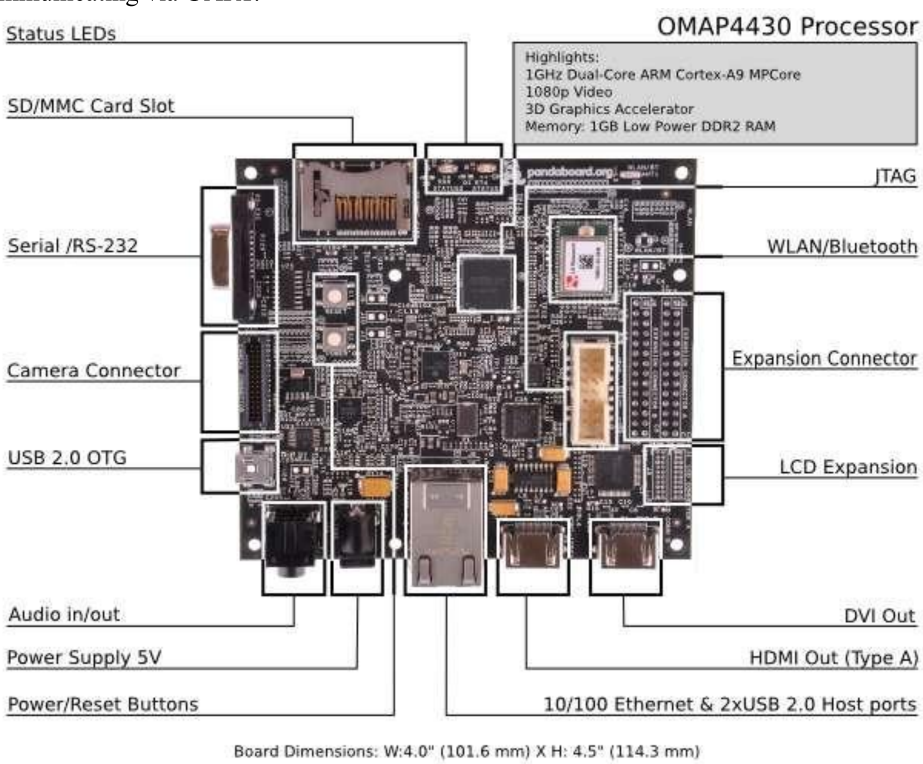


Figure 5. Top level Hardware blocks of the Pandaboard ES [8].

Since a the Pandaboard's Expansion Connector does not provide any means of temporary connection, 2x14 female pin headers were soldered to the through holes. This allows for male jumper wires to be easily connected for testing, or for this project, the place where the Kung Fu Shield can connect. This physical and electrical connection between the Pandaboard can be seen below in *Figure 6*.

Figure 6. Pandaboard with Kung Fu Shield connected via Expansion Connectors.

### *1) Kung Fu Shield Schematic and Circuitry*

After the basic requirements for the board where established, the subsystems and circuitry to be implemented were able to be designed. The most important design decision to be made was which microcontroller to be used. The STM32F405 microcontroller was chosen because of its ARM Cortex-M4 32bit processor and strong pin functionalities. It also has an internal floating point unit (FPU) which proves useful when processing the non-integer data from the sensors. The processor runs at 168MHz which is significantly more than the system requires, but is useful when running a real time operating system operating on the microcontroller and when processing larger packets of data such as those acquired from the GPS receiver. Other appealing hardware features of the STM32F405, includes 1MB of flash, communication hardware (UART, SPI, I2C, USB, etc.), 12-bit resolution analog-to-digital converter (ADC) and timer outputs [10, pp 1].

After choosing an appropriate microcontroller, each pin needs to be assigned to a particular function for the microcontroller board. Using the STM32F405 datasheet and the section providing the pin functionalities, pins can be assigned a purpose [10, pp. 45]. The datasheet provides the different pin assignments for the microcontroller package. For this project the LQFP64, 64 pin package was chosen opposed to the 100 pin package because the system did not require that many pins. APPENDIX A shows the spreadsheet used to easily and graphically plan pin assignments for this system. Since the microcontroller package has pins on all four sides, similar peripheral circuitry pins were grouped together as best as possible when assigning microcontroller pins. This method aims to have adjacent functional pins which lead to adjacent traces on the PCB layout, allowing for easier and more direct routing.

Using CadSoft's EAGLE PCB Design Software, the Kung Fu Shield was designed for PCB manufacturing. APPENDIX B contains the full schematic for the Kung Fu Shield. When creating the schematic, each individual component needed to be modeled in EAGLE if they were not already in a library. A component in EAGLE is called a "device" which is made up of a "package" and a "symbol." The package portion is the real life, physical package representation of that device, and more importantly, represents the package footprint. When designing the PCB layout for the board, only the footprints, which are the metal pads that the surface mount devices solder to, are important for the physical PCB. Often the datasheet for a device will provide recommended solder pad footprints for that device's various packages. Besides the surface mount pads, it is good practice to include a "pin 1" indicator, device name, device value and package outline for space awareness. These practices make assembling boards or replacing parts easier later on since there is no confusion when it comes to device placement. The second portion, the device's symbol, merely represents the I/O's of the device on the schematic - so its appearance has no effect on the PCB layout. Once these two entities are designed for a single device, the solder pads of the package are then connected to the pin outs of the symbol. Each device is then used in the schematic to design interconnected circuits to ultimately create a system.

Even though all the circuitry for the system is interconnected, design for the schematic was a step by step process that often focused on one circuit at a time. Many of the devices used had comprehensive datasheets that explained the function of each pin and often provided application circuits for a design starting place.

### *a. Microcontroller*

The STM32F405 required some hardware configuration prior to pin assignments. VCAP1 and VCAP2 are two pins on the microcontroller that need to be connected to 2.2 µF capacitors; these are required for the internal regulator when the microcontroller is on [10, pp. 74]. BOOT0 and BOOT1 are two pins which, based off their combined configuration, allow for where the program on the microcontroller is booted from. For this board, there is not a boot loader, there is simply a SWD programmer interface, thus the system only needs to boot from user flash memory. This boot mode is achieved by grounding both of the pins [11, pp. 47]. The reset pin for the microcontroller is active low, thus it is good practice to place a pull up resistor on the same node to prevent false resets. Last, noise and voltage ripples on the 3.3V power lines to the microcontroller, need to be decoupled by capacitors to ensure reliable signals. These capacitors need to be physically placed as close as possible to the input of the microcontroller, to reduce the noise and stray inductance that is inflicted on the trace between the two components. This issue is only observed spatially (on the PCB), so it is important to consider and compensate for these issues in the schematic, where these problems do not exist. Looking at the schematic for the Kung Fu Shield, it can be seen that there are four of the same capacitor on the input power of the microcontroller. In the PCB layout, each of these capacitors is on an individual side of the microcontroller. Since the microcontroller has power inputs on all four sides, it is necessary to have a capacitor decoupling each input. The rest of the pins, which have specific functions, were connected according to the spreadsheet mentioned before.

An external crystal oscillator was chosen to drive the microcontroller's clock. The internal oscillator of the microcontroller is often lower quality and varies with the internal heat of the microcontroller by as much as 1%; this is not often reliable for fast processing and communication. The external crystal oscillator chosen varies 0.001% for -20°C ~ 70°C operating temperatures. These statistics, in combination with crystal oscillator being isolated from heat producing components, allow it to stay stable and accurate. The only requirement for the crystal is the placement of two decoupling capacitor's to impedance match the internal capacitance of the crystal. The required capacitor values C1 and C2 can be chosen from the equation below:

$C_L = \overline{\qquad}$, $C_L$ is crystal oscillator load capacitance, C1 and C2 are decoupling capacitors [12].

The crystal oscillator's leads are then connected to the microcontroller's external oscillator pins PH0 and PH1. Even though the crystal oscillator produces an 8MHz signal, the microcontroller contains a Phase-Lock Loop (PLL) frequency multiplier which allows this externally connected oscillator to multiplied up to a 168MHz system clock [10, pp. 95].

### *b. Power Management*

Stated previously, the Kung Fu Shield must provide three different levels of voltage regulations for both the board and the Pandaboard. Since the Kung Fu Shield acts as the systems power regulation, it was important that there were mechanisms put in place to protect all the electrical hardware from the discrepancies that may occur on the power input. The sentry gun's main power source is an 11.1V, 8Ah Lithium Polymer (LiPo) battery. This battery's power and chemistry allows for minimal space within the physical system's housing while providing a high power density. These advantages come with risks such as 30C discharge capabilities and battery explosion if over discharged. To keep these risks in check the Kung Fu Shield has integrated reverse polarity, overvoltage and current surge protection. Below in *Figure 7* a model of the input protection circuit can be observed.

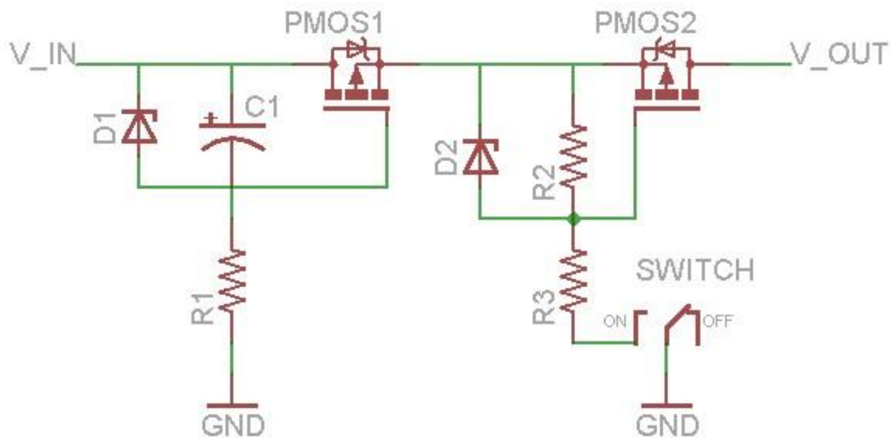

Figure 7. Model of input power protection and switching circuit.

Referring to the left side of *Figure 7* above, the reverse polarity and overvoltage protection can be seen. PMOS1 (P-Channel MOSFET) provides the reverse polarity protection by configuring it backwards to the conventional configuration. For simplicity an enhancementmode PMOS will be used. This PMOS is off until $V_{SG} = 0V$ and when $V_S > V_G$, the PMOS will start conducting. Usually this characteristic is used for power switching where a supply voltage is on the source and circuitry to be powered is connected to the drain. The high side switch is active low, meaning when the gate is high, the switch is off and when it is low the switch is on. In this case the PMOS is configured where the power supply is connected to the drain, the circuitry to be powered is connected to the source and the gate is pulled low via R1. In theory at time = 0, the PMOS is not conducting, but with this configuration, the body diode is utilized. It is a common misconception that this setup just uses the body diode for the protection, but this is not the case. A small amount of current is leaked through the body diode to the source side, effectively biasing the PMOS ($V_S > V_G$) and turning the PMOS on at time > 0. At this point in time there are two possible forward paths for the current: the forward path across the diode and the P-channel of the on PMOS. Since there is a required forward voltage drop of about 0.7V across the diode and the on P-channel has an on-resistance in the milliohms, all the current flows through the P-Channel.

In the situation of reverse polarity, where a battery is plugged in backwards, this configuration will turn the PMOS off. Let's say the drain of PMOS1 is 0V and the all the ground values are replaced with 5V. With this the gate gets pulled up to 5V, the drain is 0V and at time = 0 the source is 0V, for the same reason explained in the paragraph above. Since the gate voltage is greater than the source voltage, PMOS1 turns off at time > 0. This effectively does not allow current to flow through the system, ultimately protecting it.

The diode on the input is for overvoltage protection where, it will break down at about 15V (for this system) and force the gate of PMOS1 high, turning the PMOS1 off. The capacitor with the pull down resistor in series effectively creates a Snubber Circuit which handles current spikes that may occur due to switching or inductive loads.

On the right side of the circuit is the switching portion. When the switch is off, R3 has no effect on the circuit, so R2 effectively pulls PMOS2's gate high, turning PMOS off. Inversely, when the switch is closed, R2 and R3 create a voltage divider where the gate voltage is a fraction of the source voltage. With $V_G < V_S$ , the switch turns on, providing power for the system.

Besides these hardware mechanisms, there are a few other design features put in place to provide protection. The input voltage, which is the LiPo battery's voltage, is monitored by an analog to digital converter (ADC) channel on the microcontroller. Since the battery voltage is often much higher than the ADC's value range (0 - 3.3V), a resistor voltage divider is used to divide the voltage down to a readable voltage for the ADC. In software, this value is then scaled back up for an accurate value. A current sensor (ACS711) was placed in series with the input power path to measure how much current the hardware system was collectively using. This sensor outputs a voltage value that is measured by an ADC channel on the microcontroller. Since the current sensor's output voltage is scaled so that 55mV/A, the value is converted in software to yield the actual current usage. The microcontroller also contains an internal temperature sensor which can be sampled and provides a rudimentary indication of the power dissipated from the hardware.

Integrated power regulation occurs for three different voltage outputs: 6V for pan and tilt servos, 5V for the Pandaboard and 3.3V for microcontroller and peripheral devices. After the switching circuitry and the current sensor, the power exists on wide traces that lead to the inputs of the 6V and 5V switching regulators. The output of the 5V regulator then provides power to the Pandaboard and the input of the 3.3V low-dropout (LDO) regulator. The 5V and 6V regulators were chosen to be switching types because of their efficiency at high current demands and their ability to be more efficient than LDOs when stepping down from much higher voltages. Since these regulators are both stepping down the input voltage (i.e. 11.1V) and the regulators need to be able to supply large currents (≈ 5A max for each), switching regulators proved to be the better choice. On the other hand, these switching regulators' packages are much larger in size, due to an internal inductor opposed to the often addition of an external inductor when implementing a switching regulator. The LMZ22005 and LMZ22008 switching regulators did not require any external inductors and had easy output voltage hardware settings which are the reasons why they were chosen for this board. The 3.3V regulator was chosen to be an LDO regular because the devices on the 3.3V power line did not require much current and the voltage step down from 5V is not a big drop. LDOs step voltage down by essentially dissipating the power difference as heat. This is why several factors and tradeoffs are considered when performing regulator type selection. The tilt servo (HS-7955TG) is rated for 300mA at idle and 4.2 amps at lock/stall, where the pan servo (HS-805BB Mega Power) is rated 8.7mA at dle and 830mA at no load operation [13][14]. With these approximate max current requirements, the LMZ22008 switching regulator was chosen because it could source up to 8A. The LMZ22005 switching regulator was chosen based off the power requirements of the Pandaboard and the 3.3V LDO regulator. The Pandaboard datasheet recommends a power supply of about 4A, but practice the Pandaboard uses around 800mA at 100% CPU operation [15]. With the addition of devices being powered off the Pandaboard's USB hubs, at a maximum of 500mA, this puts the power requirement at about 2A. The Pandaboard's complete current requirement in addition to the 2A max current sourcing of the TPS75233 LDO 3.3V regulator requires about 4A total for the 5V power line, thus the LMZ22005, with a 5A output, was chosen.

Since the 6V regulator is only used to power the servos, the regulator's enable pin is connected to one of the microcontroller's digital I/O pins to allow the turning on and off of the regulator. This allows the system to save power when the servos are not being used and allow the system to turn off the regulator when an undervoltage condition occurs on the power input. The 3.3V LDO regulator has a reset pin which was connected to the board's reset line. This line allows for the Pandaboard, the reset button, and undervoltage conditions to reset both the 3.3V power regulator and the microcontroller, ultimately providing multiple and secure options for effectively resetting the system. An indication (blue) LED was placed on the output of each regulator for simple functional checking. In low power input conditions, these LEDs pulse allowing the user to observe the instability of the output power of each regulator.

### *c. Communications*

The Kung Fu Shield takes advantage of the several communication protocols that the STM32F405 supports. Although the microcontroller supports many protocols such as USB, CAN, USART, SDIO and Ethernet, this board only required UART, SPI and I2C.

The most important use of communication on the board is that between the Pandaboard and microcontroller. When choosing which protocol should be used for the interaction of the two systems several factors should be considered. The Expansion Connector on the Pandaboard allows access to several protocols supported by the OMAP processor's hardware and shares several common protocols with that of the microcontroller [8, pp. 1]. Universal Asynchronous Receiver Transmitter (UART) was chosen as the main communication between the two system because it only requires two data lines, can reach baud rates (up to 921,600 bits per second) that satisfied speed requirements, and allowed for easy software implementation. This was chosen over SPI because SPI requires two more lines (chip select and clock), and chosen over USB because of USB requires complex software and hardware configurations which provided no advantage for this particular application. In Revision 3 of the Kung Fu Shield, SPI communication hardware was added to the board to provide an alternate option for intersystem communication. This was added because of its significantly higher speed (37.5 MHz) and there was free space to incorporate the extra hardware required [10, pp. 114].

Besides choosing the protocol that would be used to carry out communications between the systems, hardware for logic translations needed to be put in place. The Pandaboard Expansion Connector operates at 0 - 1.8V logic since a lot of these pins interact directly with the Pandaboard's processor. On the other hand, the microcontroller operates on 0 - 3.3V logic. To allow proper interaction between the two, bidirectional logic translators, or level shifters, were placed on the UART and SPI lines. Not only did this handle logic differences, it also provides the busses with electrical isolation, meaning the protocol hardware's current source and sink differences will not affect that of the other system.

Besides the UART and SPI buses, used to communicate with the Pandaboard, the Kung Fu Shield provides a UART bus for the UP501 GPS receiver, a UART bus for the BlueSMiRF Bluetooth module, auxiliary UART pins, auxiliary SPI pins, and auxiliary Pins for the I2C bus. SPI is made up of Master In Slave Out (MISO), Master Out Slave In (MOSI), clock (SCK), and a Chip Select (CS) for each device connected to the bus. The auxiliary SPI shares the same SPI bus as the SPI for the Pandaboard communications. This bus sharing concept is also seen for I2C, which is made up of a Serial Data (SDA) and Serial Clock (SCL), and allows 127 devices to be on one bus without any additional lines. The bus is limited to 127 devices because the address word for I2C is 7 bits long which can contain the maximum value of 127. I2C proves to be an efficient protocol in terms of hardware but requires complex software to serve multiple devices.

### *d. LCD Screen*

The LCD screen was desired on the Kung Fu Shield because it allows for message display when debugging and a user interface. The screen itself has 16 pins: Read/Write, Register Select, screen contrast, 3.3V power (x2), ground (x2), and 8 data pins. Since the LCD screen requires 8 bits at a time and the microcontroller has limited pins, a serial-to-parallel shift register (SN74HC164) was used to interface the two components. This shift register allows data to be sent as serial (one pin), ultimately freeing up pins to be used for other functions. Even though using a shift register helps with freeing up pins, it does take 8 clock cycles to transmit a byte of data opposed to 1 clock cycle for the parallel 8 bit scheme. Fortunately this trade off does not affect system performance so it is completely acceptable. The contrast pin is used to set the LCD screen's contrast by giving a voltage value on the range of 0 - 3.3V. To allow the user to vary the contrast, a potentiometer was put in place which the user can adjust with a screw driver.

#### *e. General I/O Pins*

After all the pins required for specific functions are allocated, the remainder are used as analog inputs, digital I/Os and timer pins. Among these pins are general I/O pins designated for specific system tasks: a digital I/O for the gun's triggering and two timer (PWM) pins for the pan and tilt servo signals.

There are 6 Digital I/O pins (D0 - D5) on the board which allow for basic 0-3.3V logic interfacing for external devices. For the sentry gun, the system cooling fan's relay is controlled by a digital I/O. There are 6 Timer Pins (T0 - T5) which are capable of PWM and are useful for providing clock functionality for communication and synchronous purposes. The Timer pins are all internally connected to hardware timers, which allow for a base frequency and individual duty cycles for each of the 4 channels for a given timer. The servos use PWM signals because these signal's average voltage represent a position value. This effectively allows a digital output to act as a limited range digital to analog converter (DAC). There are 6 Analog inputs, which can measure signals on a 0 and 3.3V range. These are often used for measuring outputs of sensors that provide a scaled analog output. While providing these general I/O pin groups on the board, the STM32F405 allows nearly all of its functional pins to be used as digital I/O. Thus any of these pins, if needed, could be used as a digital I/O.

#### *d. Inertial Measurement Unit (IMU)*

In the Revision 3 of the Kung Fu Shield, a 9 degrees of freedom (DoF) IMU (LSM9DS0) was included on the board. Though not having a specific purpose yet, the IMU's accelerometer, gyroscope and magnetometer can all be used for later development. Though the sentry gun is currently a static system, it may later be integrated into a mobile platform. In this case, the IMU in combination with the GPS receiver will provide a strong tool set for navigation. Using the sentry gun's camera in combination with these navigation tools could allow advance mapping, such as SLAM (Simultaneous Localization and Mapping), to be developed on this platform.

### *2) Kung Fu Shield PCB Layout*

Once the schematic was done and the connections were checked, EAGLE placed all components on the layout. Refer to APPENDIX C for the PCB layout design. At this point Seeed Studio, a PCB manufacture, was chosen. They were chosen because their service is relatively cheap and they produce white PCBs which went well with the black PCB of the Pandaboard. At this stage is important to choose a manufacture because each manufacture provides specifications for their PCB manufacturing. This includes machine limitations, such as minimum trace width and minimum via diameter. Manufactures provide Design Rule Check (DRC) files which allow one to check if their design meets that these requirements throughout the design process. All connections between component packages are represented by "air wires," which are represented by yellow lines, showing which pins need to be connected to which pins. The outer dimensions of the Kung Fu Shield where chosen so that the board would fit on top of the Pandaboard which had several protruded features - such as the USB/Ethernet port. After the outer dimensions were set, component placement needed to be considered.

Each circuit, or group of components, needed to be placed to optimize routing to the microcontroller. Earlier it was discussed that related pins needed to be adjacent when doing the microcontroller pin assignments because it made routing easier, this is still the case. Having each circuit have a more direct path to the microcontroller allows for simpler tracing which saves time and space in the long run.

The bottom layer of the PCB was used as the board's ground plane, allowing easy ground access to any device on the board. By placing a via directly between the ground pin of a device and the ground plane minimizes ground loops, effectively decreasing stray inductance [16]. The same concept goes for any traces on the board. The traces need to be kept short as possible and should avoid being routed directly under devices to reduce inductance and electromagnetic interference (EMI). Besides parasitic inductance from the traces and ground loops, noise is also emitted from external sources and digital devices on the PCB. The switching regulators and microcontroller emit noise due to their switching frequencies. Sensitive analog circuits and RF devices, such as the GPS module, can become less accurate due to this noise. This is why the GPS module was placed far away from the other circuits on the board. Often it is good practice to partition space on the PCB for analog circuits, to reduce the effect of noise, but since there are no highly sensitive analog circuits being used in this system, this was not needed.

Simple trace characteristics must also be taken into account for each trace. Trace width dictates how much current a particular trace can support. For the power rails, the trace widths need to be reasonably large. Looking at the power input of the board, the traces must be able to support both the 5V power supply, rated at 5A and the 6V power supply, rated at 8A as well. The absolute maximum rating is 13A, but this condition will never actually occur. The traces on the inputs were designed to use as much space possible, but no real requirement was put in place. If one really wants to design for exact trace width minimum requirements based on max ratings, they could look online to find trace width calculators. Often in real implementation, these calculators are used to give an estimate of what the trace width should try to be around instead, since the widths calculated are often too big to reasonably fit on the board.

Traces also play an important role in how electromagnetics affect the signals on board - in addition to the ground loops and stray inductance. Since the board is a spatial circuit implementation, electromagnetics have to be taken into account. For higher frequency signals, an effect known as reflection can come into play if the traces are not oriented right. Reflection occurs when a signal hits a barrier, such as a sharp turn, and the signal is reflected back, distorting the signal. This can easily be minimized by making sure that traces do not change direction at, or less than, 90 degrees. This method can be accompanied by minimizing trace length in relation to width. These trace orientations are significant for high frequency signals, seen in communications, and less for ground and power traces. When powering digital signals though, it is good practice to follow the 45 degree routing rule since the power and ground are partially oscillatory. Looking at the output of a switching regulator, the power line contains oscillatory noise due to the internal switching of transistors; this is the same for all digital circuits.

When designing the PCB layout, name labelling and value labelling needs to be done. The "silkscreen" layer of the PCB contains the labelling for the board. Each component on the board was labelled for easy placement during board assembly, pins were labelled for useability, input voltage ranges were stated for the input power terminals for precaution and a board logo was added to the board. The board logo is not required but adds character. It was designed in Adobe Illustrator and contains various symbols describing the system. It is of a coat of arms made up of a panda (for the Pandaboard), crossed guns (for the sentry gun) and a shield which describes the Kung Fu Shield's functionality; a "shield" board being one that plugs onto of another board. When dealing with the silkscreen layer it was important to make sure all the text and the logo were set to "vector," this allows for cross platform plotting. If a different setting is chosen the silk screen may be printed as different size and in an offset position than what was specified in the program. This is because different companies have different machines which interpret the files differently. Once everything was placed and labelled correctly, the board then was ready to be sent off for manufacturing.

### *3) Kung Fu Shield Manufacturing*

After designing the PCB for the Kung Fu Shield, the design was then converted to the Gerber files, required by the manufacture to make the PCB, and sent out. For Seeed Studio, the minimum number of PCBs in an order was 5. This number allowed for margin of error if a board was improperly manufactured by the manufacture or if errors were made when assembling the boards. During the schematic design phase of the Kung Fu Shield, a part list was developed to keep track of the components used. Alternatively EAGLE can export a Bill of Materials (BOM) which provides a list of all the components used, their values and quantities. This makes it extremely easy when going to order parts. Refer to APPENDIX D for the Kung Fu shield's Bill of Materials.

Once the PCBs and components arrived, a solder reflow oven was used to solder the surface mount components to the board. Before taking place, much preparation had to occur. A stencil, which is a plastic sheet with each surface mount device (SMD) footprint cut out, was placed on the PCB. This stencil allows the application of solder paste to only the SMD pads. This minimizes the chance that solder will bridge two separate pads while allowing quick and easy past application. Each SMD componenet was then placed by hand in its specific location. Once complete the assembled board was reflowed in the reflow oven. After the process completes the board is looked at under a microscope to make sure no solder shorts or bridges occurred. Instead of risking solder bridges, the pad were checked under a microscope after the past was applied and the stencil was removed. Even though the past often separates during the reflow process, it is good practice to check and clear for any over saturated solder pads to reduce bridging later. The through hole components were then soldered onto the board with a soldering iron and the board was tested. The completed Kung Fu Shield connected to the Pandaboard can be seen below in *Figure 8.*

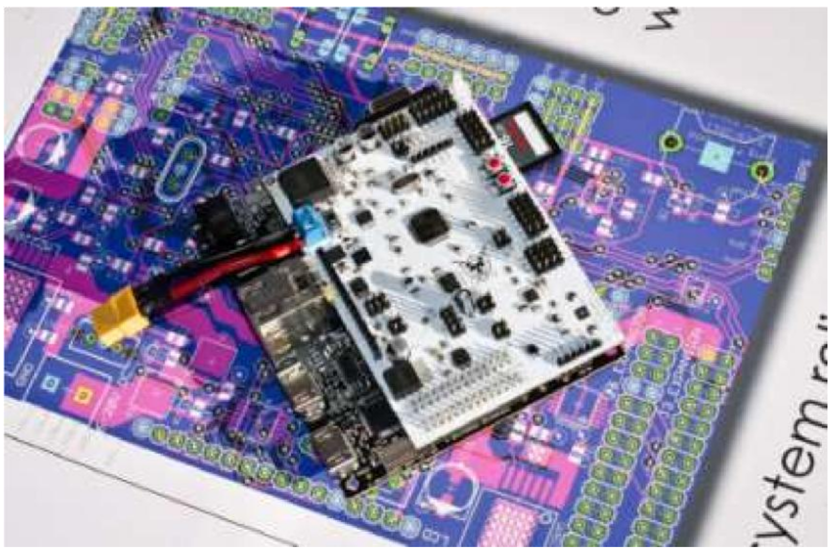

Figure 8. Complete computer hardware system for sentry gun.

## B) *Inter-System Wiring and Circuits*

Aside from the Pandaboard and the Kung Fu Shield, the system required several other circuits for basic operations. The LiPo Battery delivers 11.1V power to both the input of the Kung Fu Shield and to the Nerf gun, up on the pan and tilt assembly. For protection purposes the battery power line is connected through a 15A fuse which then is controlled by an illuminated switch that is mounted externally on the sentry gun's housing door. After the switch, the power is then run directly to the two systems previously mentioned. This circuit can be seen below in *Figure 9*.

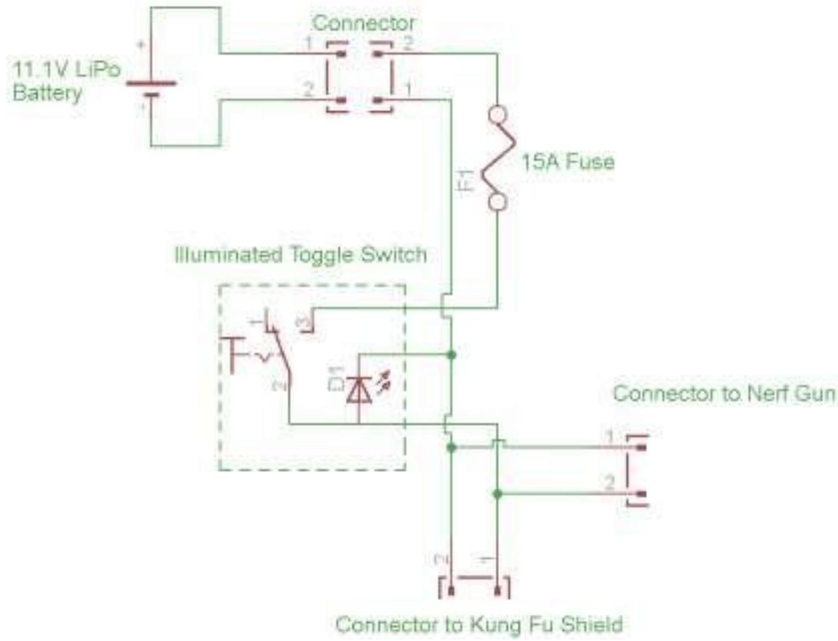


Figure 9. Basic power infrastructure wiring for the sentry gun.

The N-Strike Vulcan EBF-25 Blaster Nerf gun is an electric Nerf gun that nominally uses 9V to power the gun's motor which is used to fire the darts. The motor can be run at higher voltages which was done in this system (at 11.1V). Usually the user pulls the trigger which acts as a switch for the gun's motors. For this project, a solid state relay was put on the motor power line to function like the trigger. The relay allows for the gun's triggering to be controlled by a 3.3V signal that comes from the Kung Fu Shield and allows for electrical isolation between the two voltages. A solid state relay (SSR) was chosen because they last longer than a mechanical relay, they provide quicker switching and require less power to drive. The relay also had to be rated to handle the Nerf gun's power draw. From testing the initial peak current draw of the gun's motor is about 3A and operates at about 1A. The relay chosen (G3VM-41BR/ER) can handle 7A operating current when configured to do so. Below in *Figure 10*, the relay circuit can be seen for the Nerf gun triggering.

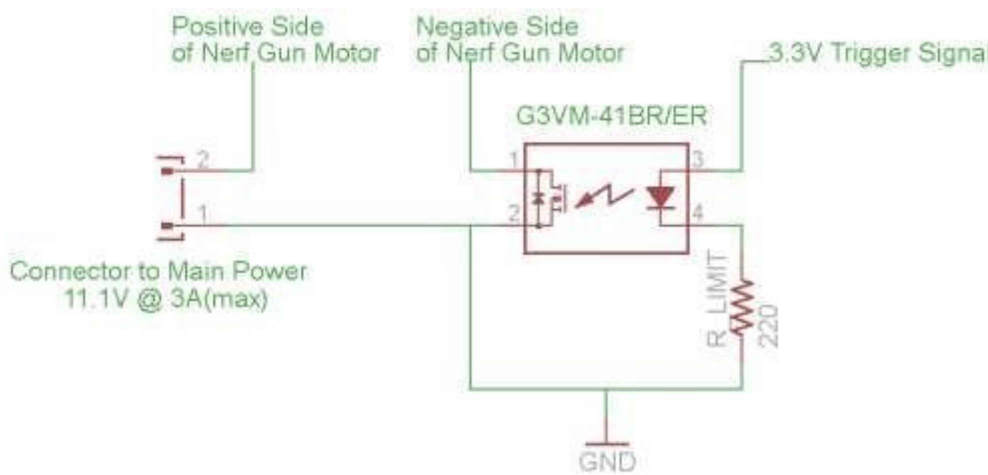


Figure 10. SSR for controlling Nerf gun motor to allow gun triggering by the Kung Fu Shield.

The relay is comprised of a LED that is optocoupled with a power NMOS that has a light sensitive gate (most likely has a phototransistor driving the gate). The LED is a current controlled device, thus a resistor in series with the LED is required to limit the current. By having the two internal component optocoupled, they are electrically isolated, meaning if one fails it will not affect the other. The motor driving side is configured to provide low side switching. This is necessary since an NMOS is the driving transistor. Having an NMOS performing this task allows for better current capabilities than PMOS while minimizing losses due to operation near ground voltage.

The sentry gun has a cooling pan integrated into the system housing which is controlled by the same relay circuit as above. The fan runs on 5V and is power via auxiliary 5V power pins from the Kung Fu shield, while being controlled by a 3.3V Digital I/O pin.

## VIII. MECHANICAL SYSTEM

The sentry gun is a physical system, one that is intended to be placed in an environment to operate. As mentioned before the system uses a pan and tilt mechanism aim the Nerf gun at the target being tracked. The system was designed to also be light, portable and durable. With the electrical subsystem fully defined the mechanical design process became much easier since there were less unknown factors that the design revolved around. Let's look at the major considerations of the design. *A. Compact and Portable:*

Since the sentry gun is to be deployed anywhere, it needs to be easily carried by a human. Light weight material needed to be chosen to fulfill this goal, but the material also needed to be durable and easy to manufacture parts with. ABS plastic was originally chosen because it is durable (flexible) and cost effective. Unfortunately the manufacturing resources at hand caused the project to be made out of Acrylic instead, which will be discussed later on in the *Results* Section. Acrylic is not ideal because it is hard making it extremely brittle and it is very expensive; opposed to ABS plastic. Though the system requires space when set up and operating, it needed to be able to minimize in size when being stored or transported. With this, Aluminum tripod legs were incorporated in the design to allow for expandable and adjustable, light weight support for the system. Since the Nerf gun is unreasonably big, it too, needs to allow the system to be as compact as possible when not in use. For this purpose, when the gun is not actively targeting it retracts flush with the front face of the system, as seen below in *Figure 11*. With the gun flush with the front face of the housing, the compact system can then be placed face down for storage and transport purposes as seen below in *Figure 11*.

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Figure 11. Compact setup of system - allows for space and carrying efficiency.

## *B. Mechanical Stability*

Several areas needed to be paid attention to when designing for the system stability. The gun on the pan and tilt assembly is approximately 8 Lbs. causing any movements by the pan and tilt assembly to have a counter torque on the physical system. For this reason the base of the system was made fairly wide to help distribute the weight, in combination with the strong tripod legs which were spaced 120 degrees apart (around the center of the system).

Once base stability was taken into account, the pan and tilt assembly was analyzed more in-depth. Since this system is designed to allow different types of guns to be mounted on the pan and tilt assembly, adjustability of the assembly needed to be incorporated since each gun will have a different center of gravity. The pan and tilt assembly was put on sliders to allow the user to shift the assembly until it is at the center of gravity for the system. The sliders for the pan and tilt assembly can be seen below in *Figure 12*.

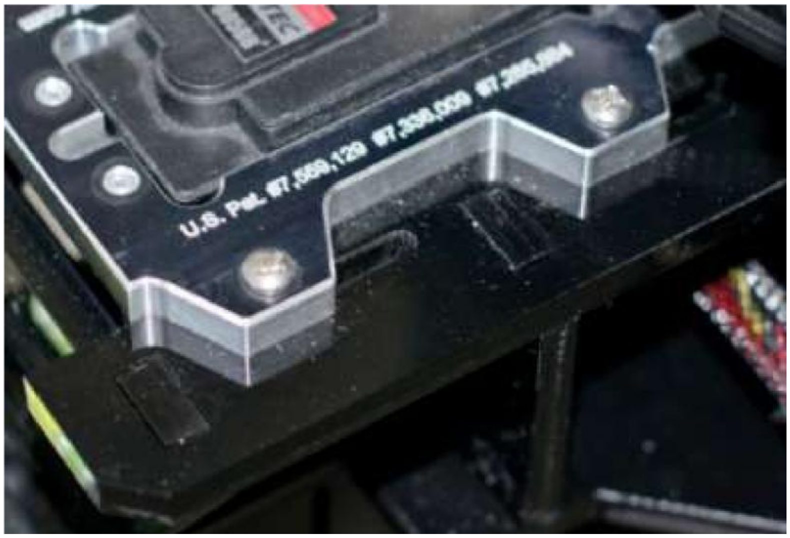

Figure 12. Pan assembly can slide over a given range for adjusting weight distribution.

The Pan and tilt assembly needed to be strong enough to support the Nerf Gun, so high torque servos were needed to rotate the large load. The pan servo assembly contained a 7:1 gear and the tilt assembly contained a 5:1 gear assembly to scale up the 333oz/in. of torque the servos could provide. By gearing up the servos, the pan and tilt step resolution increased, allowing for smaller positional steps and more accurate aiming. To effectively use the geared servos, the internal potentiometer of the servo needed to be modified. This was done by using external rotary potentiometers which were then connected internally to the servo's feedback. This modification was necessary because position feedback was now based on the gear's rotation rather than the servos' rotation, allowing accurate/compensated pan and tilt position feedback. These potentiometers featured a long shaft which was then used as the pan and tilt axles. Using the potentiometer as the axle provided less hardware and direct position feedback, opposed to having to couple it with another axle for measurements. The pan and tilt gearing, using the external potentiometer as positional feedback and as an axle, can be seen below in *Figure 13*.

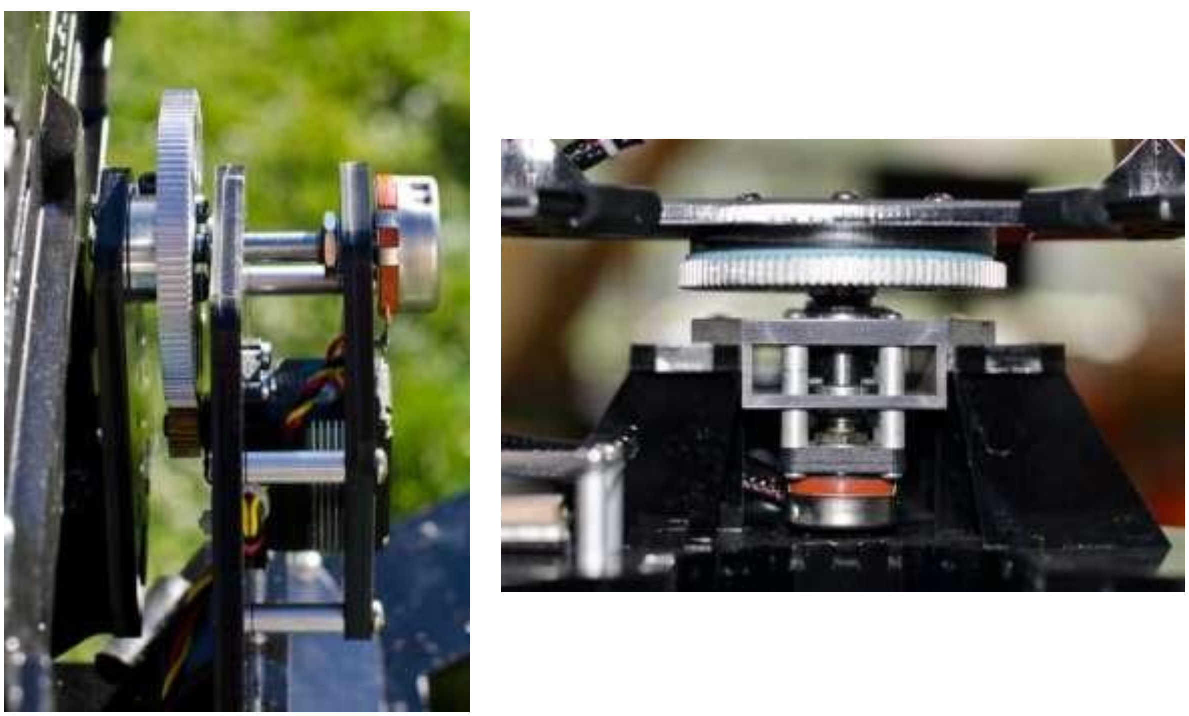

Figure 13. *Left*: Tilt assembly. *Right*: Pan assembly. Both assemblies feature potentiometers which are used as axles and for corrected feedback for the geared servos.

Since the Nerf gun was desired to be flush with the system's front face when not operating, some mechanical sacrifices had to be made. To get the gun to be able to be angled vertically downward the pan and tilt assembly need to be modified in non -ideal ways. To avoid colliding with the pan assembly base, the tilt axle, the assembly had to be positioned out in front of the pan base center. Ideally the tilt axle would be positioned directly above the pan axle, allowing for the assembly to rotate without having the strain of moving a mass that is located at a non-zero radius. Since the mass (gun) is being moved at a radius of the axle, the pan assembly and axle act as a cantilever. This causes additional stress to be put on the axle. With this problem, the pan assembly base was designed with extra support by using the large area of the pan gear. Using support pieces and a gasket, as seen above in *Figure 13*, a well dampened and secure solution for the cantilever was created. Along with the pan and tilt compensation, the base housing of the sentry gun needed to provide space for the gun barrel to reside. This task provided no issue when designing.

### *C. Mounting and External Features*

The sentry gun has several features for accessibility, device mounting and basic operations. Since the mechanical housing contains the Pandaboard and Kung Fu Board assembly, the large LiPo Battery and all the wiring in between, space and placement needed to be considered. On the right side of the housing the computer assembly was placed vertically to minimize space and to allow for easy wiring and a fan was mounted on the floor to provide the hardware with cooling. The LiPo Battery and fuse were placed on the left side of the housing to isolate them from the computer hardware, to allow for better weight distribution and to be closer to the power related system components.

On both sides for the housing are doors to access the internal components. Each door is hinged, has handles for opening and closing, and is flush when closed. The left door supports the system's main power switch, which is an illuminated toggle switch with a protective covering, and allows access to the LiPo battery and fuse. When the system is turned on, the switch is illuminated. The wiring for this switch can be seen, in relation to the power system, in *Figure 9*. On the right door is the LCD screen mount and access to the computer hardware. The LCD screen was designed to plug directly on top of the Kung Fu Shield but has been mounted on the door to provide an external user interface. This is accomplished by using a ribbon cable to connect the LCD screen to the LCD pin header on the Kung Fu Shield. Both doors and their features can be seen below in *Figure 14*.

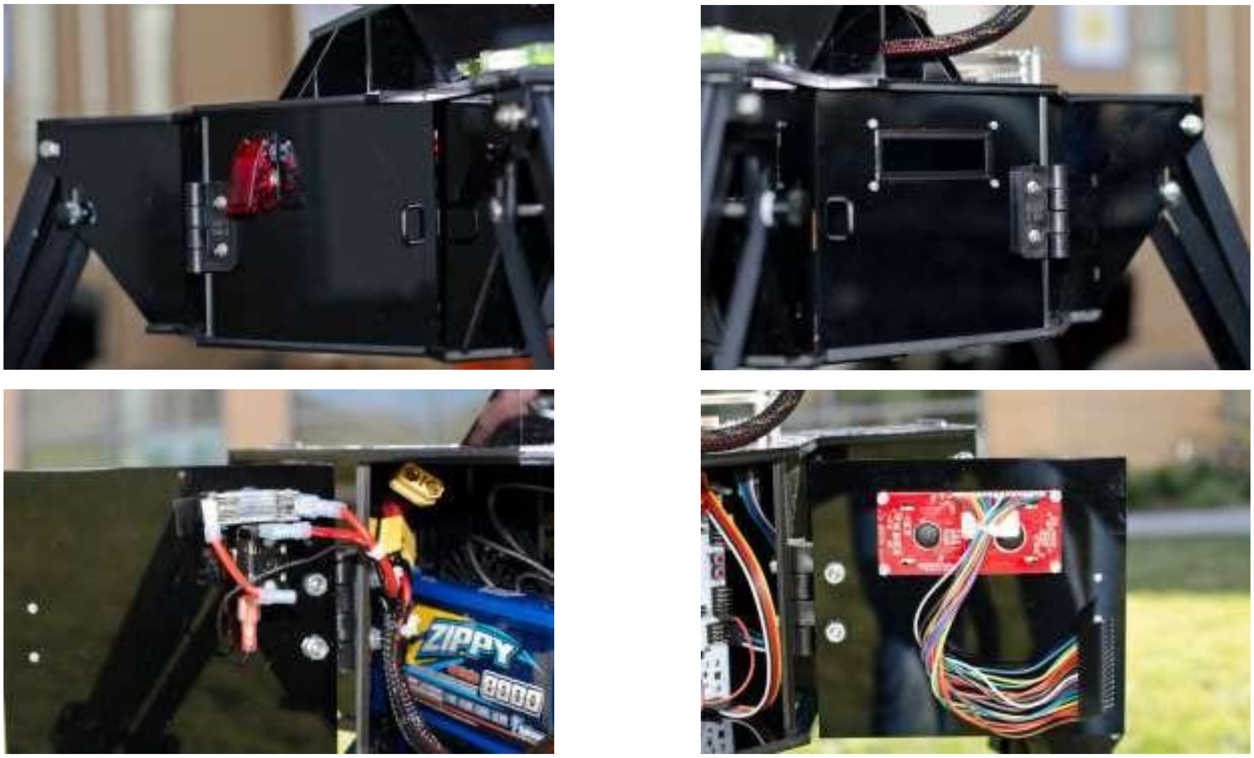


Figure 14. *Top Left*: Exterior left side door with mounted power switch. *Bottom Left*: Interior left side door containing power wiring. *Top Right*: Exterior right side door with outlet for LCD display. *Bottom Right*: Interior right side door with mount for LCD display.

Another important feature is the camera (Logitech C920). This high definition, H.264 encoding webcam was mounted on the pan and tilt as assembly. The camera was intended to be facing the same direction as the gun so aiming would involve tracking a target by adjusting the pan and tilt (gun) assembly so that the target is always in the center of the camera frame, thus gun the is pointing directly at the target at all times. The camera was mounted below the tilt platform, at the front, to allow a clear view for the gun aiming while not taking up any additional space. Since the camera was on the bottom of the tilt platform, the platform needed to be able to move without interference, so the platforms for the pan and tilt were designed to allow extra movement room for the shifting camera body. The mounted camera can be seen in *Figure 15*, when the system is off, and in *Figure 18*, when the system is actively searching and aiming.

Realized from the SolidWorks model, the Nerf gun had to be modified to allow it to point vertically down (for compact purposes). The front bottom portion of the gun had to be removed to avoid collision with the housing. Even though this system revolves around the Nerf gun, the system is designed to provide generic support for any reasonably sized gun. The tilting platform contains a vast array of mounting hold to allow for other objects to be fastened down; the Nerf gun itself is held on the tilting platform with nuts and bolts, using these mounting holes, as seen below in *Figure 15*. Besides the generic mounting holes on the tilt assembly, there are also mounting holes on the bottom of the sentry gun housing for supporting a $CO_2$ tank which is used by paintball guns. These simple features allow for mechanical system flexibility.

Figure 15. Tilt platform provides generic mounting holes for mounting other objects.

On the top of the sentry gun housing is the sensor deck. The sensor deck is an external area where environmental sensors can be placed, while being protected. The sensor deck has two female pin headers which the humidity and temperature sensor and the GPS receiver are currently connected to. These sensors and the sensor deck are covered by a clear piece of acrylic for protection, while allow for light to pass through for sensors, such as a phototransistor. The sensor deck can be seen below in *Figure 16*.

Figure 16. Sensor deck with protective clear acrylic. Currently hosting the GPS and temperature and humidity sensor.

### *D. SolidWorks Design and Manufacturing*

For a clean and professional mechanical execution, it was decided to use automated manufacturing processes for a near perfect implementation. Having access to a laser cutter (2D automated laser cutting machine), which can cut out designs from sheets of material, it was decided to use SolidWorks CAD software to design the mechanical system. Since the laser cutter can only cut parts from sheets of material (2D) the whole system had to be made of parts that could be cut from flat sheets. The part interaction with one another required for the parts to be designed with interlocking teeth; this allowed the parts to physically connect, creating a 3D structure.

Using SolidWorks not only provided an extremely accurate model for the real-life system, it also allowed for the exploration of different mechanical options and allowed for space and movement optimization before actually implementing the physical system. Since every preexisting subsystem (the Pandaboard/Kung Fu Shield combination, the LiPo battery, the Nerf gun and the servos) were able to be modeled in SolidWorks, internal placement and reconfiguration of these bodies were able to be fully considered. Many different part placements in various spots took place before the final design was cut out by the laser cutter. SolidWorks mechanical modeling allowed for the spatial testing of gun positioning requirements discussed in the previous section. This also allowed for the mechanical spacing requirement for the camera body as well.

Figure 17. SolidWorks models for the complete system. The computer subsystems and LiPo battery were incorporated for proper modeling and space optimization.

## IX. SOFTWARE

There are several software entities that have been or are going to be developed for this system. These are the embedded software on the Kung Fu Shield, the server program on the Pandaboard, and the software for client computer that can remotely control the sentry gun. Up to this report, the embedded software is done and the server and client programs have basic functionality.

### *A. Embedded Software*

The embedded software for that runs on the Kung Fu Shield needed to be able to allow for easy programming for the ARM-Cortex based microcontroller. Low-level software implementations for ARM processors are fairly complicated, thus a low-level driver abstracting operating system was used to help develop the C libraries for the board. ChibiOS real time operation system provided easy to use and well developed drivers for the STM32F407 [17]. ChibiOS also requires a small memory footprint and has fast context switching, effectively being both high level and efficient. Brian Gomberg, developer of the Aithon board, helped provide initial support of the development of the Kung Fu Shield library, having used the same microcontroller and operating system for the Aithon Board. The Kung Fu shield's C library is made up of several files to handle many of the on board operations which can be seen in *Table V* below:

TABLE V

KUNG FU SHIELD C LIBRARY FILES AND DESCRIPTIONS

| C Program Files | |
|---|---|
| analogPins.c | Configuration for ADC driver and call functions for the analog pins A0-A5 |
| bluetooth.c | Configuration for Bluetooth UART driver and read and write functions |
| digitalPins.c | Functions for read, write and mode for digital pins D0-D5 |
| extSPI.c | SPI Driver configuration for the bus used by the external SPI pins and the SPI connected to the Pandaboard |
| extUART.c | UART driver configuration for the external UART pins |
| gps.c | Configuration for GPS UART driver and functions for retrieving NMEA strings and data extraction |
| gun.c | Timer driver configuration for pan and tilt servos, pan and tilt position functions, and gun triggering function |
| I2CBus.c | I2C bus configuration and functions for read and writing to the temperature and humidity sensor |
| lcd.c | LCD screen configuration, serial character write functions |
| main.c | Contains main Kung Fu Shield Program with multiple threads for monitoring system characteristics along with handling communications with the Pandaboard |
| pandaBoardComs.c | UART configuration for communications between the Kung Fu Shield and the Pandaboard. Contains command functions for custom protocol between the two systems |
| pwrMonitor.c | ADC driver configuration for monitoring battery voltage, system current usage and core temperature |
| timerPins.c | Timer configurations for the timer pins T0-T5 |
| utility.c | Contains basic board functions for button pressing, the 6V regulation enable/disable, and the driver initializations |
| Header Files | |
| boardconf.h | Allows for selective inclusion of certain code and files. This includes GPS, Bluetooth, LCD and external pins |
| chconf.h | Allows for the configuration of ChibiOS kernel |

| | |
|---|---|
| | features |
| halconf.h | Allows for selective inclusion of certain hardware features such as USB, SDMMC, PWM, MAC, etc. |
| mcuconf.h | Allows for configuration for hardware drivers, their properties and priorities |
| utility.h | Contains the prototypes for all the files as long as wrappers for delay, read/write, and printf functions |

### B. *Server and Client Software*

The server and client software at the time of the publication of this report are basically developed and have been by Dante Gagliardi. Dante Gagliardi has created a java program that runs on the Pandaboard (in Ubuntu) which uses JavaCV, a java wrapper for OpenCV, to take in the camera's streams and send them to the client computer [18]. The server and client programs communicate over a wireless network. The client computer runs a program that is currently a simple user interface that has pan, tilt and triggering controls. Dante also has incorporated sensitivity settings for the pan and tilt movements allowing configurable system response for a given amount of button pressing.

Dante will be further developing the rest of the system's software for his senior project. This includes a more stable software system, efficient streaming of the camera feed to the client, a more useful and appealing graphical user interface (GUI), and making the server fully autonomous using OpenCV. The Lucas-Kanade method will be used to calculate the optical flow of the frames from the camera to target, track and shoot targets. Once an object that is moving is found in the frame of the camera, the Pandaboard will send positional commands to constantly try to center the object in the middle of the camera's frame by moving the pan and tilt assembly accordingly. A computer vision identification method will also be put in place so the system will have selective targeting for civilian and enemy separation.

## VII. RESULTS

With all the subsystems having significantly well-developed design processes, there were still real life obstacles that came into effect once the system was to be manufactured. With these obstacles, much was learned and overcome to develop this powerful and multidisciplinary system.

### A. *Electrical System*

The Kung Fu Shield was completely designed in EAGLE, not allowing it to be tested until the physical board was fully assembled. Unfortunately, there were design mistakes made which caused for multiple revisions of the Kung Fu Shield. The list of revision fixes and changes can be seen below for each revision.

*Revision 2:*

1. Fixed unconnected input capacitor (5V supply) to ground
2. Fixed capacitor packages:
   - 2 output capacitors of 6V supply
   - 1 output capacitor of 5V supply
   - 1 output capacitor of 3.3V supply

*Revision 3:*

1. Rearrangement of servo pin orientation
2. GPS Rx and Tx pins had to be switched
3. Replaced ACS712 (5V Supply) with ACS711(3.3V supply)
4. Added a coin cell battery holder for GPS backup power
5. Added a potentiometer for LCD Screen contrast pin
6. Fixed silkscreens: changed all to 'vector' and 'tname'
7. Removed HIH6130 temp/humdity sensor terminal
8. Modified I2C header pins
9. Logic translator was not grounded, so ground pin was connected
10. LSM9DS0 was added to board

*Revision 4:*

1. Back-up coin cell battery holder was wired backwards (now fixed)

In other design programs such as Cadence's Allegro, circuit simulation and testing can be done for the PCB layout all in the program. This would have been a better program to use, but on the other hand, it is more complex and extremely expensive.

A problem that occurred often, involved the manufacturing process for the Kung Fu Shield. Using a homemade solder reflow oven caused for discrepancies between manufactured boards, and with limited parts, non-ideal fixes had to take place. The LMZ22008 voltage regulator's package is the largest on the Kung Fu Shield and has a heat sink pad on the bottom of it to dissipate its heat into the ground plane of the board. Because of this, when reflowing the components onto the PCB, the LMZ22008 would absorb all the heat from the board, in its given area, causing itself and surrounded components to not be reflowed to the PCB. For the first board revision, this was not a problem, but for all the boards following, they would not completely reflow. It is believed that the addition of the larger surface mount capacitors added to that area of the board, for the second revision, may have caused this, but it is not certain. Consequentially, some of the surface mount components had to be hand soldered, including the pad underneath the LMZ22008. This would have been avoided if an industrial solder reflow oven was used, but one was not at available at the time.

## B. *Mechanical System*

Besides the limitations evident at the time of the mechanical design, unexpected manufacturing issues occurred when going to implement the system. Designing for the use of the laser cutter available, ABS plastic sheets were originally going to be used for systems mechanical housing. When going to cut out the parts out of the sheets, it was evident that the laser cutter could not properly cut ABS place. A week prior this project's laser cutter appointment, the laser's lens was broken causing the technicians to put in a significantly less powerful and older lens while a new lens was being ordered. Not being told this, about $100 worth of ABS sheets were gone to waste in an attempt to cut out parts. Since the laser was not powerful enough to cut through the plastic, it simply melted it. This caused a delay in the project and reconsideration of the material being used. Since many prior projects have been successfully built out of Acrylic parts, cut from the laser cutter, it was the most secure option at the time. Acrylic being expensive ($200 for this project) and brittle, it was less than ideal but would have to do. Using the Acrylic did work, and is the current material that the system's housing is made out of. Going back to its brittleness, weeks after the system was built, the system was not properly setup and was knocked over causing a portion of the housing to break. Fortunately, this was able to be fixed. This would have not happened if the housing was made from a softer and flexible material like originally intended and if the system was place like it was designed to be. Besides the unpredictable limitations that occurred, inhibiting planned manufacturing, the mechanical system had very few problems due to its well rounded and thorough design in SolidWorks.

### *C. Software Implementation*

Even though software is free and can be instantly fixed, there were some obstacles that were run into. For the embedded software on the Kung Fu Shield, ChibiOS was useful by abstracting the low-level hardware drivers of the ARM processor, but it required time to learn. Though it uses Doxygen to document all of the code, the documentation does not give proper explanations of what each thing actually does. This lack of information, along with a small supportive community, ChibiOS was hard to start programming with. With the help of Brian Gomberg and constant low-level file reading, after a couple of months after initially starting with ChibiOS, it was finally able to be used for developing the Kung Fu Shield's library.

For the server and client software systems, several problems creating basic programs occurred. Initially, getting OpenCV to install on the Pandaboard was difficult. Though the Pandaboard is a reasonably powerful development platform, it has a small support community and has a lot of underlining short comings that are not often evident. For the camera streaming, the Pandaboard cannot properly handle the frames with OpenCV. It is believed that this is because the camera outputs a H.264 encoded stream and the OMAP processor of the Pandaboard does not support or does not come with the codec software to process the camera feed. This causes an extremely low frame rate, that of 1-2 fps, when displaying the camera feed in the GUI. Currently the camera feed has been left out of the GUI until the cause of this problem can be found and resolved.

### *D. Complete System Implementation*

Through conscious and well planned design of the individual subsystems, and how they interact with each other, the Remote/Autonomous Sentry Gun Platform was a success. This system proves that a complex and sophisticated system can be created by combining electrical, mechanical and software systems. This project was executed in a professional manner and will be a strong based for future development. The complete prototype can be seen in *Figure 18* below. Since several of the system's specifications were not met for this revision, the system will be passed down to future senior project groups were they will be given a particular upgrade task which they will have to successfully complete in a professional manner. Not only will the prototype allow for a flexible and autonomous system, which is practical in modern day military applications, it will also provide students with an interest in robotic systems a great development platform which will let them explore their interests while also helping them develop as a professional engineer.

Figure 18. Complete Remote/Autonomous Sentry Gun Platform.

# APPENDIX A — KUNG FU SHIELD MICROCONTROLLER PIN ASSIGNMENTS

TABLE VI
KUNG FU SHIELD 64 PIN STM32F405 MICROCONTROLLER PIN ASSIGNMENTS

| Pin Number | Pin Name | Chosen Pin Function | On Board Purpose |
|---|---|---|---|
| 2 | PC13 | Digital I/O | 6V PWR Enable |
| 3 | PC14 | Digital I/O | Bluetooth Enable |
| 4 | PC15 | Digital I/O | GPS Enable |
| 5 | PH0 | Digital I/O | Crystal Osc. input 1 |
| 6 | PH1 | Digital I/O | Crystal Osc. input 2 |
| 8 | PC0 | ADC123_IN10 | Battery Voltage Measure |
| 9 | PC1 | ADC123_IN11 | Current Sensor Measure |
| 10 | PC2 | ADC123_IN12 | Analog Pins |
| 11 | PC3 | ADC123_IN13 | Analog Pins |
| 14 | PA0 | ADC123_IN0 | Analog Pins |
| 15 | PA1 | ADC123_IN1 | Analog Pins |
| 16 | PA2 | ADC123_IN2 | Analog Pins |
| 17 | PA3 | ADC123_IN3 | Analog Pins |
| 20 | PA4 | SPI1_NSS | External SPI Header: NSS |
| 21 | PA5 | SPI1_SCK | External SPI Header: SCK |
| 22 | PA6 | SPI1_MISO | External SPI Header: MISO |
| 23 | PA7 | SPI1_MOSI | External SPI Header: MOSI |
| 24 | PC4 | Digital I/O | LCD Shift Register Clock |
| 25 | PC5 | Digital I/O | Serial to LCD Shift Register |
| 26 | PB0 | Digital I/O | Gun Trigger Enable |
| 27 | PB1 | Digital I/O | LCD R/W Enable |
| 29 | PB10 | I2C2_SCL | External I2C Header: SCL |
| 30 | PB11 | I2C2_SDA | External I2C Header SDA |
| 33 | PB12 | Digital I/O | Digital Pin 0 |
| 34 | PB13 | Digital I/O | Digital Pin 1 |
| 35 | PB14 | Digital I/O | Digital Pin 2 |
| 36 | PB15 | Digital I/O | Digital Pin 3 |
| 37 | PC6 | USART6_TX | External UART Header: TX |
| 38 | PC7 | USART6_RX | External UART Header: RX |
| 39 | PC8 | TIM8_CH3 | Pan Servo PWM Signal |
| 40 | PC9 | TIM8_CH4 | Tilt Servo PWM Signal |
| 41 | PA8 | TIM1_CH1/Digital I/O | PPS from GPS Receiver |
| 42 | PA9 | USART1_TX | Pandaboard Header UART: TX |
| 43 | PA10 | USART1_RX | Pandaboard Header UART: RX |
| 44 | PA11 | TIM1_CH4/Digital I/O | User Button |
| 45 | PA12 | Digital I/O | Digital Pin 4 |
| 46 | PA13 | SWDIO | Load Pins (Programmer) |
| 49 | PA14 | SWCLK | Load Pins (Programmer) |
| 50 | PA15 | Digital I/O | Digital Pin 5 |

| | | | |
|---|---|---|---|
| 51 | PC10 | UART4_TX | External Bluetooth Header: TX |
| 52 | PC11 | UART4_RX | External Bluetooth Header: RX |
| 53 | PC12 | UART5_TX | External GPS Header: TX |
| 54 | PD2 | UART5_RX | External GPS Header: RX |
| 55 | PB3 | TIM2_CH2 | LCD RS (Register Select) |
| 56 | PB4 | TIM3_CH1 | Timer Pin 0 |
| 57 | PB5 | TIM3_CH2 | Timer Pin 1 |
| 58 | PB6 | TIM4_CH1 | Timer Pin 2 |
| 59 | PB7 | TIM4_CH2 | Timer Pin 3 |
| 61 | PB8 | TIM4_CH3 | Timer Pin 4 |
| 62 | PB9 | TIM4_CH4 | Timer Pin 5 |

# APPENDIX B — KUNG FU SHIELD SCHEMATIC

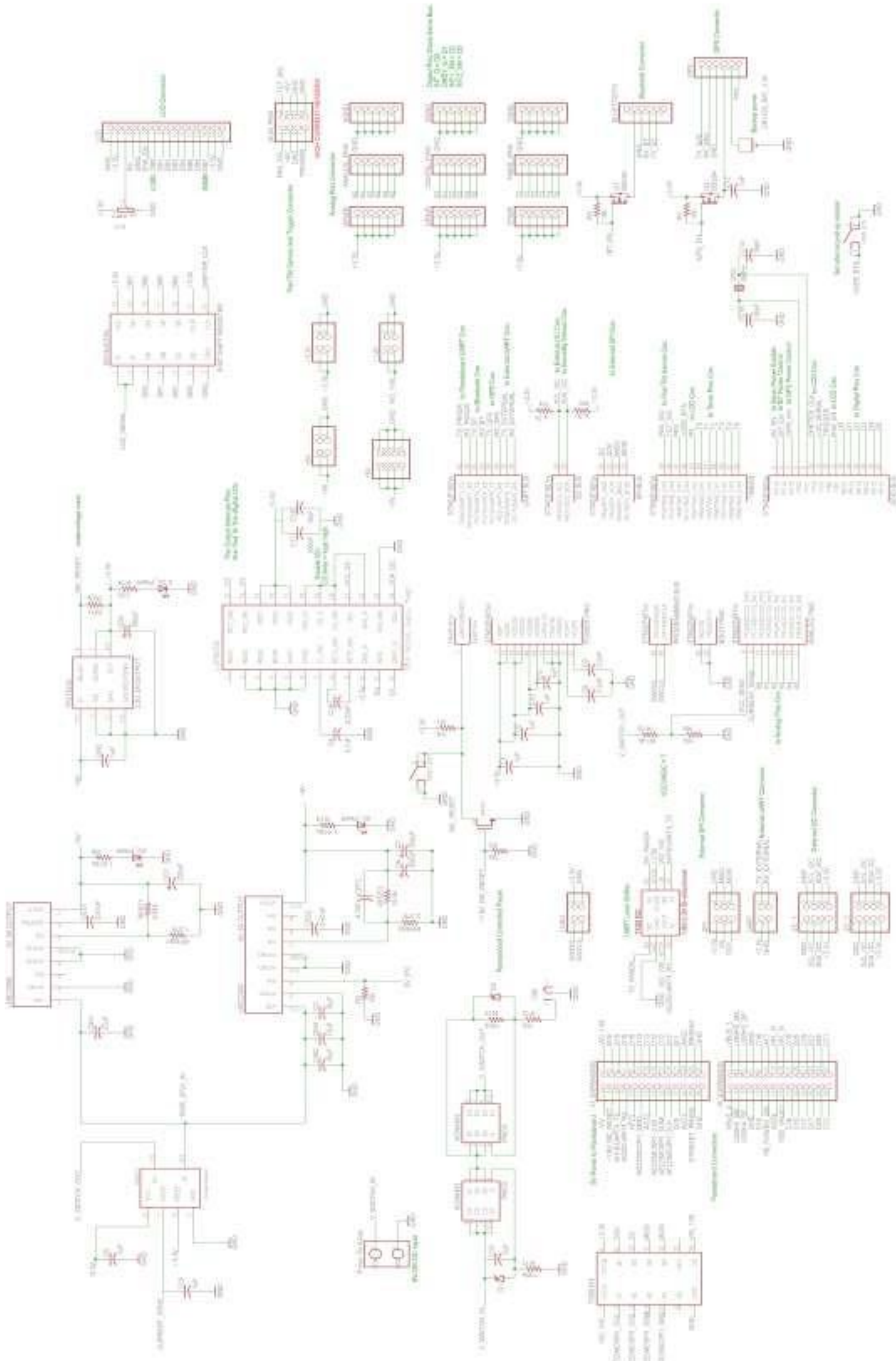

Figure 19. Kung Fu Shield board schematic designed in EAGLE.

APPENDIX C — KUNG FU SHIELD PCB LAYOUT

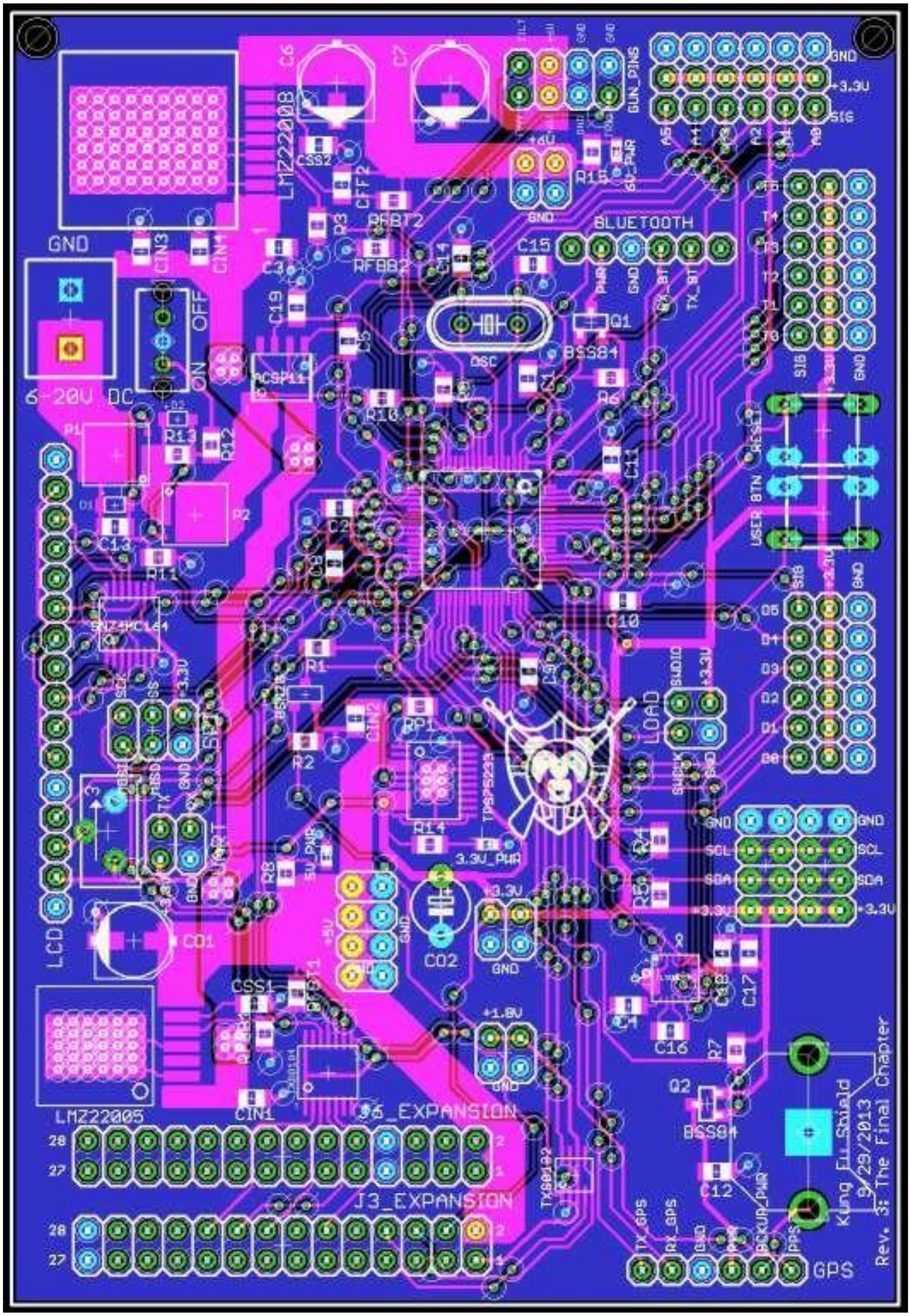

Figure 20. PCB layout in EAGLE for the Kung Fu Shield.

## APPENDIX D — KUNG FU SHIELD BILL OF MATERIALS

TABLE VII KUNG FU SHIELD BILL OF MATERIALS

| Part | Link | Quantity | Description |
|---|---|---|---|
| | | | |
| **CAPACITORS** | | | |
| .1uF Capacitor 805 | http://www.digikey.com/product-detail/en/CGA4J2X7R1H104K125AA/445-6957-1-ND/2672975 | x8 | |
| 10uF Capacitor 805 | http://www.digikey.com/product-detail/en/C2012X5R1V106K125AC/445-14418-1ND/3956084 | x4 | |
| 1nF Capacitor 805 (1000pF) | http://www.digikey.com/product-detail/en/C2012X7R2E102K085AA/445-2277-1-ND/789786 | x1 | |
| 330uF Capacitor Alum Can | http://www.digikey.com/product-detail/en/EEEFTC331XAP/P15095CT-ND/2796946 | x2 | Panasonic size D8 |
| 2.2uF Capacitor 805 | http://www.digikey.com/product-detail/en/C2012X7R1C225K125AB/445-1420-1-ND/569086 | x2 | |
| 36pF Capacitor 805 | http://www.digikey.com/product-detail/en/C0805C360J5GACTU/399-9229-1-ND/3522747 | x2 | |
| 4.7nF Capacitor 805 (4700pF) | http://www.digikey.com/product-detail/en/C2012X7R2A472K085AA/445-1341-1-ND/567650 | x1 | |
| 22uF Capacitor 805 | http://www.digikey.com/product-detail/en/C2012JB1E226M125AC/445-11475-1-ND/3953141 | x1 | Voltage rating of 25V for vin |
| 1uF Capacitor 805 | http://www.digikey.com/product-detail/en/C2012X5R1E105K085AC/445-7624-1-ND/2733696 | x1 | |
| 220uF Capacitor Alum Can | http://www.digikey.com/product-detail/en/ECEV1AA221XP/PCE3352CT-ND/361693 | x1 | Panasonic size D8 |
| 100uF Capacitor Alum Can | http://www.digikey.com/scripts/DKSearch/dksus.dll?Detail&itemSeq=131232006&uq=635053037558321655 | x1 | Panasonic size C |
| 0.47uF Capacitor 805 | http://www.digikey.com/product-detail/en/C2012X7R1E474K125AA/445-1353-1-ND/567602 | x2 | |
| 4.7uF Capacitor 805 | http://www.digikey.com/product-detail/en/C0805C475K9PACTU/399-3134-1-ND/551639 | x1 | |
| 0.22uF Capacitor 805 | http://www.digikey.com/product-detail/en/C0805C224K4RACTU/399-8051-1-ND/3471774 | x1 | |
| **LED, TRANSISTORS, ETC.** | | | |

| | | | |
|---|---|---|---|
| Blue LEDs 603 | http://www.digikey.com/product-detail/en/LB%20Q39E-N1P135-1/475-2815-1-ND/2176354 | x3 | 3.3V_PWR, 5V_PWR, 6V_PWR |
| BSN20 | http://www.digikey.com/product-detail/en/BSN20,215/5681658-1-ND/763485 | x1 | NMOS for Reset |
| DZ2J150 | http://www.digikey.com/product-detail/en/DZ2J150M0L/DZ2J150M0LCT-ND/2269089 | x2 | Zener diode for reverse polarity protection |
| Crystal Oscillator | http://www.digikey.com/product-detail/en/9B-8.000MEEJB/887-1233-ND/2207653 | x1 | 8MHz extern clock |
| BSS84 | http://www.digikey.com/product-detail/en/BSS84/BSS84CTND/244297 | x2 | PMOS for power control |
| | | | |
| **RESISTORS** | | | |
| 10k Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF1002V/P10.0KCCT-ND/119248 | x7 | |
| 4.7k Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF4701V/P4.70KCCT-ND/1746872 | x2 | |
| 1.075k Resistor 805 (1.07k Resistor 805) | http://www.digikey.com/product-detail/en/ERJ6ENF1071V/P1.07KCCT-ND/118966 | x1 | |
| 60.4k Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF6042V/P60.4KCCT-ND/119487 | x1 | |
| 100k Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF1003V/P100KCCT-ND/119551 | x2 | |
| 255 Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF2550V/P255CCT-ND/118785 | x1 | |
| 1.575k Resistor 805 (1.58k) | http://www.digikey.com/product-detail/en/ERJ6ENF1581V/P1.58KCCT-ND/119014 | x1 | |
| 1.07k Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF1071V/P1.07KCCT-ND/118966 | x1 | |
| 2.37k Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF2371V/P2.37KCCT-ND/119065 | x1 | |
| 5.62k Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF5621V/P5.62KCCT-ND/119176 | x1 | |
| 15.4k Resistor 805 | http://www.digikey.com/product-detail/en/ERJ6ENF1542V/P15.4KCCT-ND/119315 | x1 | |

| | | | |
|---|---|---|---|
| 250k Resistor 805 (249k) | http://www.digikey.com/product-detail/en/ERJ6ENF2493V/P249KCCT-ND/119664 | x1 | |
| 10k Potentiometer | http://www.digikey.com/product-detail/en/3386H-1103LF/3386H-103LF-ND/1088508 | x1 | Rev 3. BOTTOM SIDE OF PCB |
| | | | |
| **IC's** | | | |
| LMZ22005 | http://www.digikey.com/product-detail/en/LMZ22005TZ%2FNOPB/LMZ22005TZ%2FNOPBND/2626438 | x1 | 5V power |
| LMZ22008 | http://www.digikey.com/product-detail/en/LMZ22008TZ%2FNOPB/LMZ22008TZ%2FNOPBND/2626435 | x1 | 6V power |
| TPS75233 | http://www.digikey.com/product-detail/en/TPS75233QPWPRQ1/296-15280-1-ND/568094 | x1 | 3.3V power |
| TXS0102 | http://www.digikey.com/product-detail/en/TXS0102DCTR/296-21978-1-ND/1632671 | x1 | Logic Translator for UART |
| SN74HC164 | http://www.digikey.com/product-detail/en/SN74HC164PW/SN74HC164PW-ND/1570750 | x1 | Shift Register |
| STM32F405 64PIN | http://www.digikey.com/product-detail/en/STM32F405RGT6/497-11767-ND/2754208 | x1 | Microcontroller |
| AON6403 | http://www.digikey.com/product-detail/en/AON6403/7851339-1-ND/3060880 | x2 | PMOS for reverse polarity protection |
| ACS711 | http://www.digikey.com/product-detail/en/ACS711ELCTR25AB-T/620-1371-1-ND/2470595 | x1 | Current Sensor |
| LSM9DS0 | http://www.digikey.com/product-detail/en/LSM9DS0TR/49713902-1-ND/4311634 | x1 | IMU: Accel, Magn, Gyro |
| TXB0104 | http://www.digikey.com/product-detail/en/TXB0104PWR/296-21929-1-ND/1629282Detail&itemSeq=137262123&uq=635160142321 865737 | x1 | Logic Translator for SPI |
| | | | |
| **CONNECTORS** | | | |
| Buttons | http://www.digikey.com/productdetail/en/TL1105F250Q/EG1828-ND/42761 | x2 | reset and user btns |
| Pwr Switch | http://www.digikey.com/product-detail/en/OS102011MS2QS1/CKN9542-ND/1981413 | x1 | |
| Pwr Terminal (ED500/2DS) | http://www.digikey.com/product-detail/en/ED500%2F2DS/ED1623-ND/33934 | x1 | |

| | | | |
|---|---|---|---|
| Male Pin Headers 1x40 (General Pins) | http://www.digikey.com/scripts/DkSearch/dksus.dll?WT.z_header=search_go&lang=en&keywords=A26509-40ND&x=0&y=0&cur=USD | x2 | |
| High Power Male Pin Headers 1x50 (Servo Pins) | http://www.digikey.com/product-detail/en/TSW-150-07-LS/SAM1031-50-ND/1101377 | x1 | |
| 1x6 Femal Headers | http://www.digikey.com/product-detail/en/PPTC061LFBNRC/S7004-ND/810145 | x2 | Bluetooth and GPS |
| | | | |
| Double sided Male Pin Headers (2x14) | http://www.pololu.com/catalog/product/1065 | x2 | For Pandaboard expansion headers |
| CR1220 Coin Cell Battery Holder | http://www.digikey.com/product-detail/en/3001/3001KND/227442?cur=USD | x1 | external battery holder, |
| | | | |
| **BATTERIES** | | | |
| CR1220 3V Coin Cell | http://www.digikey.com/scripts/DKSearch/dksus.dll?Detail&itemSeq=137268646&uq=635160613285835715 | x1 | GPS backup battery |
| | | | |
| **NOT AVAILABLE** | | | |
| 1x16 LCD Header | http://www.digikey.com/scripts/dksearch/dksus.dll?vendor=0&keywords=S7014-ND&cur=USD | x1 | only available in Bulk (1000) |