Steel Wire-Rope Inspection Tool

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***Abstract* — This report contains information pertaining to the research, design, and testing of the Steel Wire-Rope inspection tool. The Steel Wire-Rope inspection tool is a tool that will be able to navigate a Steel Wire-Rope on its own while performing a visual inspection. Overviews of the Visual Inspection tool, Hall-effect Sensor tool, Stepper Motor system, and Power system are provided. The Steel Wire-Rope inspection tool was proposed by the United Launch Alliance and is an inter-disciplinary project involving 3 Mechanical Engineering teams and one Computer Engineering/Electrical team. The Steel Wire-Rope inspection tool hopes to reduce inspection costs and labor and offer an alternative method of Steel Wire-Rope inspections.**

***Index terms* — Hall effect, Hall effect devices, microcontrollers, pulse width modulation, regulators, Stepper motor, torque.**

I. INTRODUCTION

The United Launch Alliance has developed an emergency egress system to safely and quickly evacuate launch crews in case of emergency. The egress cables are situated on level 12 of the Crew Access Tower (CAT), 172 feet above the Space Launch Complex 41 pad deck at Cape Canaveral Air Force Station and allow the crew to evacuate the CAT quickly to a landing zone. The system developed was a Zip Line with 4 parallel cables, that support 20 personnel escape harnesses, allowing the crew to safely evacuate to a landing zone approximately a quarter mile away. The Emergency Egress System zip line cables must undergo periodic inspection to ensure no damage to the cable has occurred due to any potentially damaging events (launch, hurricane, lightning strike, etc.).

The current method of inspection requires personnel to do a visual inspection of the entire length of the cable, while riding the cable, which can be both tedious and expensive. Working in conjunction with 3 Mechanical Engineering Senior Design Teams, we have developed an automated wire-rope inspection tool that will traverse the entire length of the cable performing a visual inspection, in addition to checking for cracks or chips in the steel wire rope using an array of hall effect sensors. By using an automated tool to inspect the steel wire-rope, significant man hours and dollars can be saved.

II. OVERVIEW

The Steel Wire-Rope Inspection Tool is an idea that was originally proposed by our Sponsor, United Launch Alliance. The objective is to look for signs of damage to the wire including Foreign objects the cable, broken strands of cable, signs of electrical damage, and excessive corrosion. The Emergency Egress system cable specifications are detailed in table 1. The device must complete inspection of all 4 cables in 4 hours and will only be required to descend the length of each cable. Our primary goal was to design a tool that can inspect the cables to the Emergency Egress System zip lines at the Crew Access Tower and flag likely spots for damage requiring further inspection. This project is a multi-disciplinary project where we are working in conjunction with three separate mechanical engineering senior design teams. The inspection tool will be comprised of multiple sub-systems: Cameras for a visual inspection, Hall Effect Sensor, Motor and Controls, and Power. Cameras will be used to provide a visual inspection of the cable as the tool traverses the wire. Using an array of hall-effect sensors designed to detect flux leakage in the metal wire, potentially damaged spots will be flagged. The motor and controls subsystem will consist of a Stepper motor controlled using a microcontroller utilizing pulse width modulation. All mechanical design aspects including but not limited to, chassis, wheel clamps, housing, torque requirements etc. will be handled by the Mechanical Engineering teams we are working with. Our scope in the project is to provide the sensors to the mechanical teams, programming modular controls for the motors, handling battery and power requirements, as well as data storage and interpretation. Some of the key factors when considering design options include size, weight, modularity, portability, and durability.

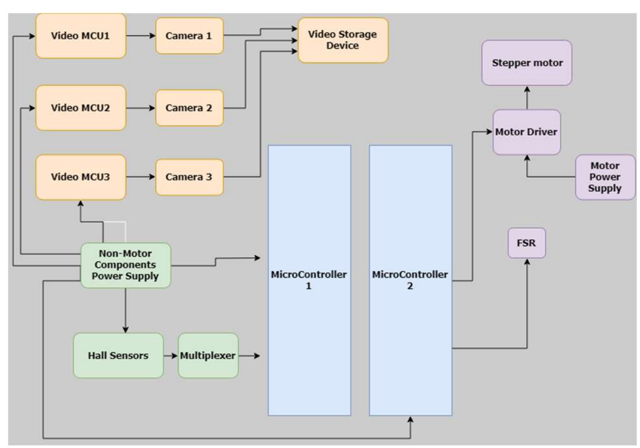

Fig. 1 Overview block diagram of the Steel Wire-Rope Inspection Tool.

III. HARDWARE DESIGN

The Steel Wire-Rope Inspection Tool consists of four major subsystems, referred to as the Visual Sensor system, Hall-effect system, power system, control system. In order to begin approaching the design the cable specifications must be considered.

Egress Cable Specifications	
Length	1319 ft.
Average Grade	14%
Cable	IWRC 6x19 Steel Wire Rope
Cable Thickness (Diameter)	3/4 inch.

Table 1. Cable specifications

The Hall-effect and Control Systems are controlled by their own microcontrollers, separating the power from the more vulnerable components. The microcontrollers making up the nucleus of the control system are two ATMega328 chips, one responsible for providing Pulse Width Modulation (PWM) to drive the motor, the second responsible for receiving and storage of data from the Hall-effect sensor system. A stepper motor moves one step when the direction of current flow in the field coils changes, reversing the magnetic field of the stator poles. By sending a PWM signal from the microcontroller unit to the Stepper motor the Stepper motor is able to convert the input pulses in the form of square waves into a defined exact increment in shaft position. Each input pulse moves the shaft through the defined fixed rotation angle proportional to the input pulse allowing for a high-level of control and precision.

The second microcontroller is used to control and receive data from the array of hall sensors used for magnetic flux leakage to detect cracks or chips in the wire. The working principle of the magnetic flux leakage using hall sensors requires that the steel wire-rope be saturated with magnetic field lines, which is accomplished by placing a permanent magnet block in close proximity to both the wire and the Hall sensor. The video system consists of multiple cameras arranged around the wire-rope to provide multiple views of all sides of the wire-rope. The power system must be on-board and portable, the motor will be powered by a separate battery to meet the higher needs, and the other on board electrical and non-motor components will be powered by a second smaller Lithium Ion battery.

A. Motor and Control System

The Motor that was selected for the Steel Wire-Rope Inspection tool is the 23HS45-4204S Stepper motor, a High Torque Nema 23 100mm Stepper Motor with a step angle or 1.8° and a Holding Torque of 3.0Nm(425oz.in). Weighing 1.8kg with a recommended operating voltage of 24-48V and a current rating of 4.2A this powerful motor will be used to turn a gearbox developed by the mechanical teams to achieve our necessary torque requirements to traverse along the steel wire. The motor will be driven by a DM542 digital stepper driver. The motor driver consists of two connectors, P1 for control signal connections and P2 for power and motor connections. P1 configurations are made up of 6 pins in total.

Two Pulse signal pins (PUL+ and PUL-) used to represent the pulse signal used to drive the motor. Two direction signal pins (DIR+ and DIR-), a signal with low and high voltage levels representing the two directions of motor rotation. Note that rotation direction is also related to motor-driver wiring, exchanging the connection of two wires for a coil will reverse motor direction. The last 2 pins on the P1 configuration are used to enable and disable the driver (ENA+ and ENA-). The P2 configuration is made up of 4 pins in total. The first pin +V is connected to the Power Supply (20-50VDC), the second GND is used for Power Ground, the A+ and A- pin is used for motor phase A, and similarly the B+ and B- pin is used for motor phase B.

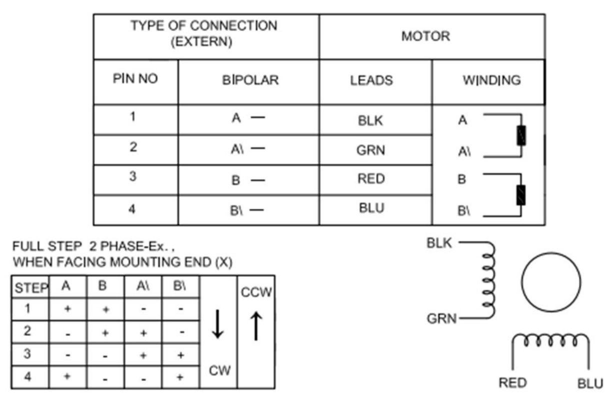

Fig. 2 Overview of 23HS45-4204S Stepper Motor configurations. [3]

The ATMega328p microcontroller will be used for programming the motor controls. The ATMega328p consists of 20 input and output pins, 14 digital and 6 analog. It features 32kb of Flash memory for program storage and 2kb of RAM memory. The ATMega328p was selected due to the affordability and familiarity as well as ample documentation existing reducing the difficulty in integrating hardware components and troubleshooting. By integrating our Motor controller with the Microcontroller unit run time instructions and controls are stored and interfaced with the Motor. By determining the amount of necessary turns based on step angle we can appropriately program the motor to turn precisely as far as we need to meet the run distance of approximately 1320 feet. By sending HIGH and LOW pulses to a digital I/O pin selected to be the pulse pin on the microcontroller the stepper motor will turn.

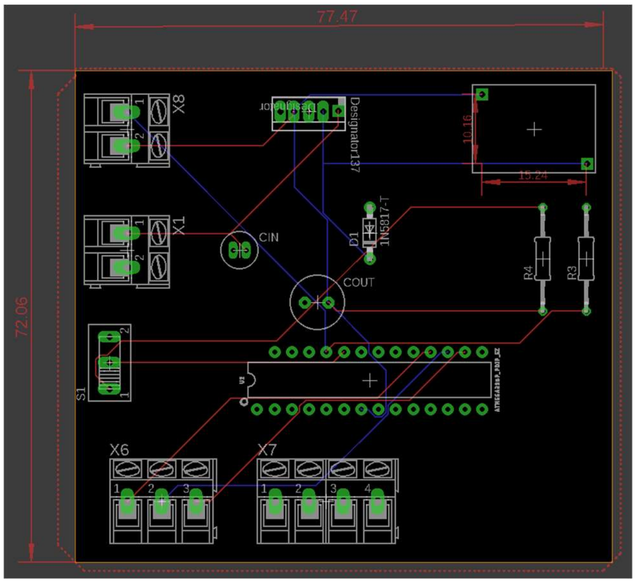

Fig. 3 Motor Control Board

The motor can be started and stopped with a simple switch incorporated into the system. In addition to stopping the motor by coding in a set run time, or by turning off the switch, an alternative method of stopping the motor was developed through the use of a Force Sensitive Resistor. When the inspection tool reaches the end of the wire and hits a stopping point the force sensitive resistor will be touched and acts as a switch to turn the motor off.

Below we calculate desired Speed and Runtime Values for our Stepper Motor given: Step Angle of 1.8°, Shaft radius of 5mm, desired Linear velocity of 0.868 ft/s.

$$StepsPerRevolution : \frac{\frac{360}{1Rev}}{\frac{Degree}{Step}} = \frac{\frac{360}{1Rev}}{\frac{1.8}{1}} = 200\frac{Step}{Rev}$$

$$Desired\ Linear\ Velocity = 0.868 ft/s$$
$$Linear\ Velocity = Angular\ Velocity(\omega) * radius(r)$$
$$Linear\ Velocity = \frac{2\pi}{time\ 1\ rev} * radius$$

Using our desired Linear Velocity we can calculate the necessary time for 1 revolution to occur and subsequently determine the necessary Revolutions Per Minute (RPM) to meet our desired run time. First we determined that the time for 1 Revolution to occur t= 0.03619 seconds. Then we multiply this value by 60 seconds to determine that a run speed of 2.1714 RPM is necessary to achieve our desired Linear velocity of 0.868 ft/s.

Knowing that our Stepper Motor speed is controlled through the microcontroller via steps per second and having calculated the RPM necessary to achieve our desired Linear Velocity we can use the RPM value to determine precisely how many steps per second the motor needs to turn in order to achieve a Linear Velocity of 0.868ft/s

$$Revolutions\ Per\ Minute = 60 * \frac{Steps\ Per\ Second}{Steps\ Per\ Revolution}$$

Given previously calculated values of 2.1714 RPM and 200 Steps per Revolution

$$Desired\ Steps\ Per\ Second = 7.238\ steps\ per\ second$$

B. Hall Effect System

The design of the Hall sensor elements consists of the attachment of the input voltage to a regulated 5 Volt power supply. Then the connection of a .01 µF capacitor between the ground and input voltage pins. Next for lower noise on the analog output pin an additional RC filtering circuit was elected to further reduce the bandwidth and lower the noise seen by the microcontroller analog input pin. The magnet and sensor will be moving relative to the wire rope longitudinally and in the case where there is no fault in the wire rope the magnetic flux lines will pass through the inside of the ferromagnetic strands composing the wire rope, and the sensor will have low input.

If there is a fault, however, then the magnetic flux lines will be distorted since the magnetic permeability of the fault is much smaller than that of the wire rope material. Therefore, the magnetic resistivity will increase in the fault area. Since the wire rope is saturated the flux lines will have to expand into the more magnetically resistive air. When the sensor is passing over the location of the damage an electrical signal will be produced due to the received magnetic flux. This electrical signal will be largest when the sensor is closest to the area of the fault. The corresponding electrical signals can be stored for further evaluation by trained expert wire rope inspectors to determine the severity of the damage and if the wire rope should be retired. One of the benefits of magnetic flux leakage is that it can catch several types of damage such as broken wires, abrasion, and corrosion on the surface as well as on the interior of the rope.

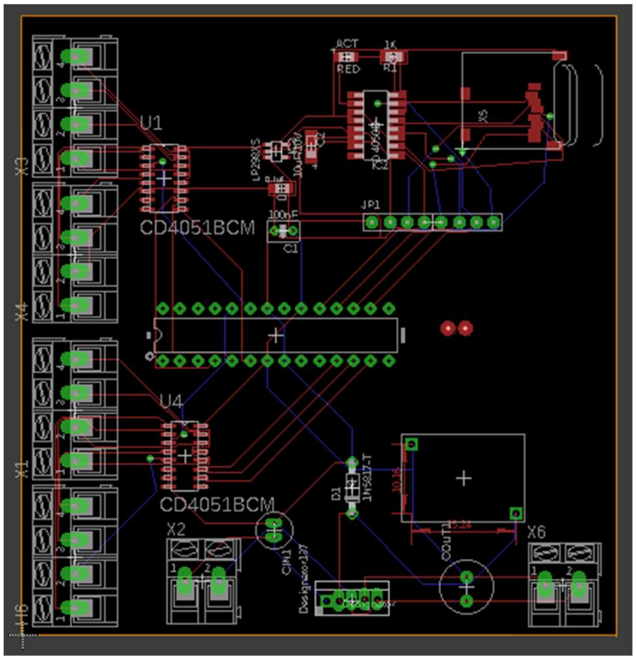

Fig.4 Hall Sensor MCU Board

The DRV5056-Q1's to be used in the Zip line inspection tool are continuous-time, ratiometric, linear Hall-effect sensors. They receive a five Volt input from the voltage regulator and accurately produce a ratio of the five Volt input based on an applied magnetic field to the sensor. If there is no magnetic field applied to the sensor then the analog voltage output from the sensor will be the quiescent voltage which is 0.6 Volts for the DRV5056- Q1. The output pin of the DRV5056-Q1 will be directly connected to the analog input pin of the microcontroller for reading at the optimal clock rate. This value will then be converted to a digital value for storage in a variable. How the data is stored from the hall sensor is important because when there is a fault and the hall sensor reads this as a high voltage there needs to be a correlation between the video input from the cameras and the location of the high voltage from the Hall effect sensor. When storing each value from each hall sensor the time at which the reading was taken will be stored alongside it in an array format such that the values can be downloaded for further analysis. Ideally it is desired that the sensor voltage data be graphed versus time and to be viewed in conjunction with the camera footage to make the identification of faults on the zip-line easier to locate. In figure 4 below the Hall Sensor layout and PCB board is shown.

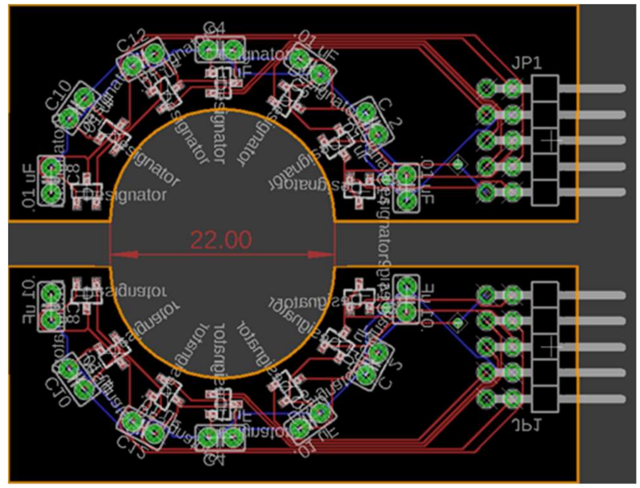

Fig.5 Hall Sensor Design

C. Visual Sensor System

The Visual Sensor System will consist of 3 cameras each controlled by their own separate development board for data acquisition. The three cameras will be spread equidistantly around the cable to ensure that all portions of the cable are in view. The system will be comprised of three Raspberry Pi 3 model B+ controlling three Raspberry Pi Camera Module V2 that will output to their own removable USB storage devices. The visual system is the main focus of the inspection for ULA which means that getting quality video is a high priority. In order to get quality video, the camera systems will need to be recording at a high enough resolution, frame rate, and quick enough shutter speed to ensure quality video as a deficiency in any of those three traits will have a noticeable effect on the end video. Because of the need for high quality video, the system was split into the three separate camera systems to ensure that the processors used would have enough power to achieve the video quality desired.

For the Visual Sensor System, we compared three different microcontrollers/microprocessors. We looked at the Arduino Uno which used an ATmega328P, the BeagleBone Black which uses an AM335x 1GHz ARM Cortex A-8, and lastly the Raspberry Pi which uses a Broadcom BCM2837B0 Cortex-A53. The ATmega328P was our initial choice as it was cheap and easy to use with extensive libraries however after early testing it became apparent that it would not be powerful enough to suit our needs even when controlling only a single camera. The AM335x with the BeagleBone was the next choice as it had slightly more processing power and ability compared to the Raspberry Pi as a whole, however issues with getting cameras to work with the system and outdated and not as extensive libraries caused an issue in development. The final choice was the Raspberry Pi which thanks to more extensive libraries and camera modules designed specifically for it allowed development to move forward and allowed for more control over the camera system than allowed with the other options.

Two main visual sensors were considered for the system, the first was the ArduCAM-Mini-5MP-Plus OV5642 Camera Module and the other was the Raspberry Pi Camera Module V2. The ArduCAM-Mini-5MP-Plus OV5642 is a general purpose high definition 5MP SPI camera. The camera module integrates the 5MP OV5642 CMOS image sensor, along with adding additional hardware to assist with the image processing and handling and reducing the complexity of the camera control interface. The main reason this camera module was considered in the first place it that it gave us the ability to use multiple cameras with a simple Arduino using an ATmega328P. Even with this advantage and ease of use with the microcontroller the performance was not up to our needs when used with the ATmega328P. This led then to acquiring a more powerful processor to run the modules but even with the open source libraries there were issues getting them to integrate with the other processors tested for the Visual System.

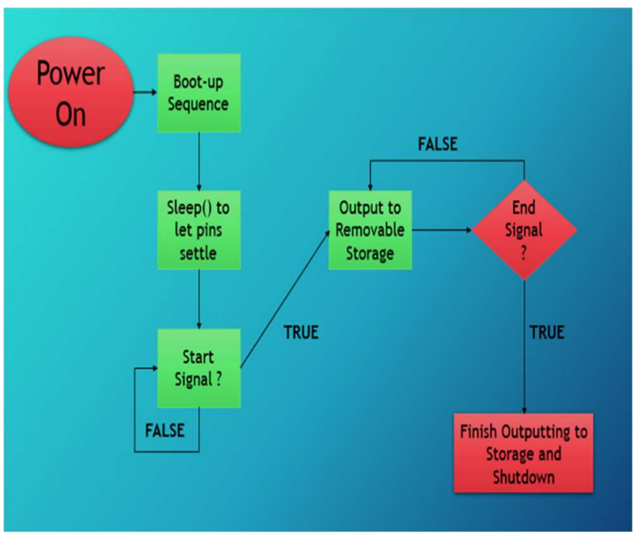

Fig. 6. Software Flowchart for Visual Sensors

Once development moved to the Raspberry Pi the Pi Camera Module V2 was considered as it was made specifically to interface with the special CSI slot on the Raspberry Pi. Even with the loss of the extra processing power on the OV5642 Camera Module the Pi Camera Module is able to produce high quality 1080p video with the drawback of only being able to use one camera module per Raspberry Pi board. This drawback however was greatly overshadowed by the consistent high-quality output and the ease of use thanks to the extensive existing libraries while also allowing much more control over the video feed and quality then afforded by the OV5642. Because of this the decision was made to use three Raspberry Pi Camera Module V2s each controlled by their own board.

IV. PARTS SELECTION AND APPLICATION

A. Microcontrollers

The main functions of the microcontrollers are to process input data recorded by the Visual and Hall sensor packages, along with storing program memory and controlling Pulse Width Modulation to drive the stepper motor. Familiarity, core size, peripherals required, speed, power consumption, flash memory, cost, available libraries, processing power, and programming language are some of the key factors we considered when selecting the microcontrollers to use. Keeping this in mind two microcontrollers were considered, the Atmel ATmega328p-PU microcontroller and the Texas Instruments MSP430G2553.

The MSP430G2553 is a member of the Texas Instruments MSP430 family of ultra-low power microcontrollers. It is designed with five combined low-power modes to optimize battery life and features a 16-bit RISC CPU, 16-bit registers, a Low Supply Voltage Range (1.8V-3.6V), Ultra-low power Consumption (Active mode: 230uA at 1MHz, 2.2V), and is programmed in the familiar C language. However, the libraries are not as extensive, nor catered towards PCB design, and incorporating analog inputs and the initial setup requires much more coding in comparison to the ATmega328P.

The ATmega328P- PU produced by Atmel is an 8-bit low-power CMOS microcontroller that combines an instruction set with 32 general-purpose working registers directly connected to the Arithmetic Logic Unit. This allows two independent registers to be accessed in a single instruction executed in one clock cycle. The ATmega328P is one of the most versatile and popular choice in microcontroller projects and as a result has extensive libraries and documentation allowing for user-friendliness. The 8bit AVR RISC based microcontroller combines 32KB ISP flash memory with read-write capabilities and additional features include 2KB SRAM, 23 general purpose I/O lines three flexible timers/counters, internal and external interrupts, and is programmed using the C language.

Ultimately, it was decided that benefits of extensive libraries, higher Flash and RAM, ease of testing, and versatility of the ATmega328P provided optimal function for our needs in comparison to the MSP430.

B. Hall Effect Sensor

When considering Hall effect sensors for the application of detecting flux leakage due to material loss the main factors to consider are the Hall effect sensor's magnetic sensitivity, output characteristics and operational range. It is the desire for the Hall effect sensor's magnetic sensitivity to be as large as possible due to the fact that the potential cracks in the wire rope may not be very large and therefore only allow minimal flux leakage. It is also the desire for the Hall effect sensor to have easy to connect and interpret output which could be directly connected to a microcontroller for voltage data acquisition and storage. Therefore, an analog output Hall effect sensor which varies its output to a ratio of its supply voltage should work well in this capacity. Also, it is important that the operational range of the Hall effect sensor be wide such that the zip line inspection tool can distinguish 30 between detections of a large amount of flux leakage from the wire rope, which would suggest more serious fault, and detections of smaller amounts of flux leakage which would suggest a less serious fault. Other features of the device are important as well, such as operating temperatures, quotient voltage, and polarity, but these are the features that will be the main decision-making points on which Hall effect sensor is chosen. After much searching the TI DRV5056-Q1 Automotive unipolar ratiometric Linear Hall effect sensor was chosen based on its high sensitivity, low quiescent offset voltage, and uni-polarity. The DRV5056-Q1 is a 3-pin linear Hall Effect sensor with fully integrated signal conditioning, temperature compensation circuits, mechanical stress cancellation, and amplifiers. The device operates from 3.3-V and 5-V (±10%) power supplies, measures magnetic flux density, and outputs a proportional analog voltage that is referenced as VCC.

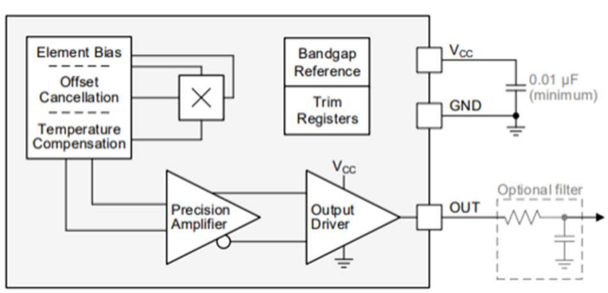

Fig. 7 Functional Block Diagram of DRV5056-Q1. [1]

In order to saturate the wire a permanent magnet is incorporated into the design it must have a surface field strength of at least 1500 Oersted and be similar in size and dimensions to the ¾'' steel wire rope to be inspected. The SBCC6-OUT Nickel-Plated Neodymium magnet with a surface field of 4260 Gauss was chosen to saturate the steel wire rope.

Due to the high number of Hall Effect Sensors used in our sensor array and the limited Analog inputs to our microcontroller an 8-channel Analog Multiplexer was incorporated into our design. The multiplexer selected was the CD4051 by Texas Instruments. Through the utilization of a multiplexer we are able to select which of the 8 inputs from the various hall effect sensors we wish to read at a certain time. By looping through the 8 inputs we are able to achieve readings from all of the Hall effect sensors.

C. Motor and Motor Driver

The 23HS45-4204S Stepper motor, a High Torque Nema 23 100mm Stepper Motor with a step angle or 1.8° and a Holding Torque of 3.0Nm(425oz.in) was the motor selected to be used. In order to achieve our 4 hour run time for all 4 cables the desired operating speed is 0.868 ft./s which will require a torque of 384 oz.-in. We had to work in close proximity with the Mechanical Engineering Teams to determine a suitable motor to meet their needs. It was carefully considered whether the increased weight of a motor with higher torque rating was worth the trade off since the entire system needs to be kept as lightweight as possible. It was ultimately decided that a Nema size 23 motor combined with a gear box to be developed by the mechanical teams would meet the torque needs to traverse the wire-rope.

To drive the Motor and act as a bridge between the Motor and the Microcontroller the 23HS45-420S will be paired with a DM542 digital stepper driver. The advantage of using a digital stepper driver versus a traditional analog stepper driver is that the DM542 can drive a stepper motor at much lower noise, lower heating, and smoother movement. This makes it the ideal choice for high requirement applications such as our own. The DM542 motor driver is suitable for stepping motors in the range of 17 to 34 NEMA size. It features Anti-resonance to provide optimal torque and nullify mid-range instability, it is suitable for 2-phase and 4-phase motors, additionally it features Over-voltage and over-current protections. A typical stepping system configuration including a stepper motor, stepping driver, power supply, and microcontroller used for pulse generation is shown in Fig. 8 below.

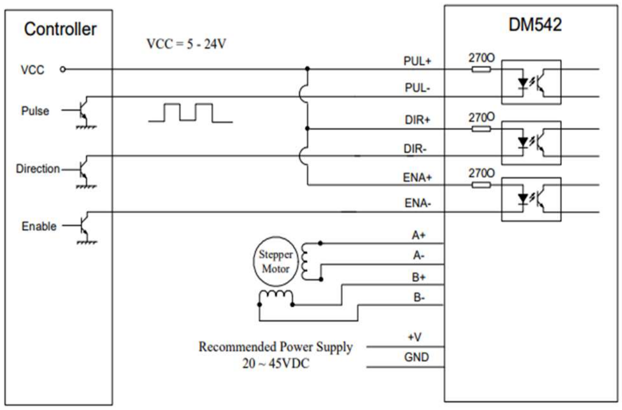

Fig. 8 Typical stepping system configuration using DM542 Motor driver. [2]

Additionally, a Force Sensitive Resistor was incorporated into the design to stop the motor once the inspection tool has reached the end of the Wire-Rope. The TTP223 touch pad detector IC offering 1 touch key was selected. It has key features of Low power consumption and a wide operating voltage and can be used in DC and AC applications.

D. Cameras

Three ArduCAM-Mini-5MP-Plus OV5642 Camera Modules were selected for our Visual Inspection. The ArduCAM-Mini-5MP-Plus OV5642 is a general purpose high definition 5MP SPI camera. This camera modules integrates the 5MP OV5642 CMOS image sensor, along with adding additional hardware to assist with the image processing and handling and reducing the complexity of the camera control interface. It also gives it the advantage of being able to be easily interfaced with many different development platforms and hardware while having an existing open source library for the software to operate the camera module. The large advantage we were interested in though is that it allows for multiple cameras to be connected to a single microcontroller.


Fig. 9 ArduCAM 5MP mini with OV5642 Visual Sensor

E. Power System

The goal for the portable power supply for the zip line inspection tool was to have separate portable rechargeable batteries for the mechanical design team's motor power and electrical design team's electronic peripheral and sensor power. This section is an overview of the wire rope inspection tool's power system design for all of the electrical design team's circuit peripherals.

Given that there is limited space and weight available for the crawler to carry these were the most important attributes of the portable rechargeable batteries considered for the design. LiPo batteries were deemed the best chemical composition of battery for the purposes of the design due to their superior charge density and voltage ranges.

Feature	**Custom Li-Ion 18500 Battery**	Lectron Pro Lipo Battery **#6s5200-509**
Voltage	7.4V	22.2V
Capacity	2800mAh	5200mAh
Battery Dimensions	106mm x 38mm x 22mm	136mm x 45mm x 51mm
Max charge rate	3 hrs.	2 hrs.
Weight:	220g	659g

Table 2. Comparison of Li-Po batteries considered

Since both of the batteries considered met the weight and dimension design requirements of the inspection tool the more powerful and larger lasting Lectron Pro was selected to ensure that the zip line inspection tool didn't lose power halfway through an inspection.

Additionally, a voltage regulator had to be selected. As with any battery, the output voltage is unregulated and varies which demands the employment of a regulating circuit to provide a constant output voltage to all of the electrical peripherals. All of the electrical design team's components operate at a nominal voltage of five Volts and so a high efficiency switching voltage regulator whose output was five volts and was capable of delivering upwards of one Amp was sought.

Feature	**LM2575**	LMR14010
Input Voltage Range	4 – 40 V	4 – 40 V
Output Voltage	5 V	0.765 V to 30 V
Max Output Current	1 A	1 A
Output Options	Fixed	Adjustable

Efficiency	77%	80%
Operating Temperature	-40 - +125 C	-40 - +125 C
Switching Frequency	58 kHz	0.7 MHz

Table 3. Comparison of Switching buck regulators

VI. CONCLUSION

The design and development of the Steel Wire-Rope inspection tool highlights and demonstrates the technical skills that the team members have acquired and developed in their time as Engineering students at the University of Central Florida. The development provided valuable lessons in PCB design, interdisciplinary teamwork, time management, and problem solving all important things to take into the industry post-graduation. The opportunity to gain hands on PCB design experience as well as engaging with multiple engineering disciplines will prove to be invaluable. Through the two semesters of development many hurdles were faced but our team was able to remain level-headed and work together to overcome these obstacles.

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