Video Image System Implementation on the Track Crawler Robot

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ABSTRACT

The Track Crawler robot at the Center for Vehicle Systems and Safety, in Blacksburg, Virginia, is a state of the art project that is designed to examine the underbelly of trains while in a dormant state. The idea and motivation for this project comes from scenario that a train would arrive at a station, after completing a journey, and the Track Crawler robot would navigate under the train to examine the systems within to allow engineers to determine if parts of the train require extra maintenance before its next journey. Consequentially, the majority of the Track Crawler project is dependent on the proper function of the robot's video imaging system. This system allows engineers to have a clear view of the underbelly of the theoretical train, in a space that is otherwise not accessible to view by the naked human eye. On the current model of the Track Crawler, the robot is fitted with up to 3 GoPro Hero 8 Black Cameras, aligned in a linear fashion, to work as the robot's video imaging system. One of the major problems with this system, however, is the vibrations the system is put under while the robot is in motion, and effect it has on the quality of videos. Therefore, the scope of this report will be to give the reader an idea of how the problem was identified as well as outlining possible solutions for a new visual imaging system that includes a new standard video camera, an infrared camera, and an adjustable light sensor. All of these proposed additional systems will work to remedy the original problem of maintaining high video quality at high frequency vibrations, and this report will serve as a foundation for implementing a more detailed design in the future.

To my friends, family, and those who kept believing in me

ACKNOWLEDGMENT

To My Friends & Family,

Without a doubt, this Spring 2022 semester has been filled with ups and downs. Still, it is unbelievable to me, the support system that I have been blessed to lean back on since coming here to Virginia Tech almost 2 years ago to date. When I made the decision to come to Virginia Tech, and furthermore join the Center for Vehicle Systems and Safety as an Undergraduate Researcher, to be honest, I really did not know the full scale of what I was getting myself into. At the time, I was a wide-eyed engineering student who knew he wanted to make an impact on the research community in Blacksburg, and eventually, around the world. While exuberantly enthusiastic about my, then, future in undergraduate research, I was very noticeably nervous about the journey I would soon embark on. But, something that was unbeknownst to me was the friends I would make, not only at the Center for Vehicle Systems and Safety, but around the Blacksburg, Virginia community that would always be there in times of laughter or hardship. It is something that I will forever be in your debt with, and from the bottom of my heart, I truly need to say, thank you.

In addition to my friends around Virginia Tech, I would be remised if I didn't address the elephant in the room about the journey, I recently had the blessing of embarking on. Coming from both of my parents being members of the Divine 9, it was always something I knew I wanted to be a part of when I came to college, however, one of the main things I needed to constantly refine if I were to choose this way of life would be my "why" question. It had to be more than the reason of "My Dad is a Que" or "My Mom is Greek", I needed to develop my own motivations to pursue the lifestyle that I wanted. Therefore, when people ask me the question "Why did you choose Omega?", my answer to such is "I didn't, Omega chose me." To my Chapter Bruhz of the Everloving, Everlasting, Eta Lambda Chapter of the Omega Psi Phi Fraternity Incorporated, thank you for your love and support during this semester. RQQ to the good Bruhz from Spring '22!

Dwight Walter Jones II

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Chapter 1 – Introduction

1.1 Track Crawler Overview

The Track Crawler robot originated as a senior design project in the Virginia Tech Mechanical Engineering department sponsored by the Center for Vehicle Systems and Safety. The motivation of the project was to develop a robot platform that has the ability to capture images, videos, or scans of a train's underbody and its visible components.

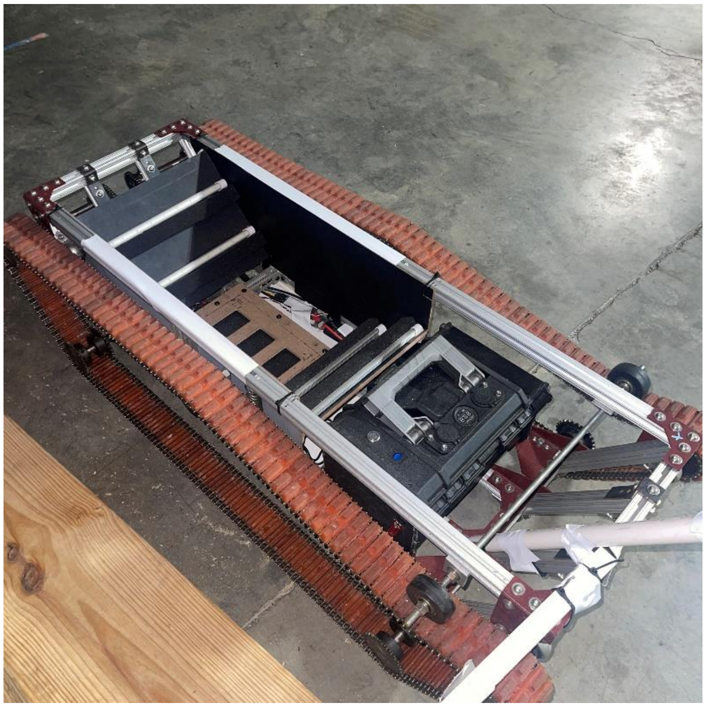

Figure 1: The Track Crawler at the Center for Vehicle Systems and Safety

Figure 1 shows a picture of the current model of the Track Crawler Robot at the Center for Vehicle Systems and Safety. This is the model that was adapted from the aforementioned senior design project by undergraduate mechanical engineering students at Virginia Tech.

1.2 Major Components of Track Crawler

The major components of the Track Crawler robot include the current video imaging system, comprised of up to 3 GoPro® Hero 8 Black Cameras, the radio transmission system, responsible for communicating with the robot's control system. This is done with a DX6 Radio Transmitter by Spektrum®. Furthermore, the rest of the Track Crawler is made up of the robot's motor, and locomotion system by utilization of caterpillar tracks. For the scope of this report, we will focus on the components that make up the video imaging system and how to improve the system under high frequency vibrative forces, experienced under the robot's locomotion, and recommendations on how to add an infrared imaging system as well as an adaptive lighting system.

Chapter 2 – Current Imaging System

2.1 Overview

The purpose of this chapter is to give an overview of the current video imaging system present on the Track Crawler Robot as of right now. As previously mentioned, the robot has the capability to house up to 3 GoPro® Hero 8 Black Cameras, however, under high frequency vibrations, the image stabilization technology built within the GoPro system is not able to detect such vibrations. The following table goes into detail the specifications of the GoPro cameras used on the current iteration of the Track Crawler Robot.

Sensor:	**Sony IMX277**
Sensor Size:	**1/2.3”**
Aperture (f-stop):	**f/2.8**
Focal Length:	**2.92mm**
Dimensions:	**66.3W x 48.6H x 28.4D**
Battery:	**1220mAh, Lithium Ion**
Still Image Resolution:	**12 Megapixels**
Connectivity:	**Wi-Fi, Bluetooth, GPS**

Table 1: GoPro® Hero 8 Black Technical Specifications

Given the technical specifications of the currently used cameras, the advantages of using such cameras are as follows:

1. GoPro® Cameras are known for their ruggedness and waterproof capability. This makes

them good for situations in which the environment the camera being used in would be otherwise harmful to the internals of the camera

2. The high resolution and high framerate of the GoPro® Hero 8 Black is second to none at its highest resolution setting, the camera can shoot at 4K at 60 frames per second. At its highest frames per second setting, the camera can record at 1080p at 240 frames per second.

3. The Hero 8 Black has the capability to record metadata, from the cameras sensors, that includes GPS information in which the user can derive position, acceleration, altitude, speed, and more.

4. Wi-Fi connection capability allows for the user to control multiple cameras at once which allows the user ease of access to controlling the 3 cameras.

2.2 Current Problems

While it is important to outline the current pros of the advantages of the imaging system, the scope of this report will mainly focus on the disadvantages experienced by the operator. Outlining both is important to eventually developing the reasoning behind the eventual recommendation that will be made later in the report. The disadvantages of the current imaging system are as follows:

1. The Hero 8 Black has a fixed focus lens which means the minimum distance the subject can be from the lens, in order for the subject to be in focus, is 12 inches.

2. Relative to outside conditions, the Hero 8 Black has a very low operating range. According to the GoPro® Hero 8 Black Operator's Manual, the camera only has an operating temperature of 14° F to 95° F. For situations in which, at the least, the ambient outside temperature is above or below this range, the camera will not be able to operate at an adequate level.

3. For longer term evaluation, in which the Track Crawler Robot plans to operate in, the GoPro's battery life is less than ideal. With the restriction to only operate for approximately 50 minutes of continuous recording, this would contradict the Track Crawler's objective of examining the underbody of a railcar without direct knowledge of any discrepancies. 50 minutes of continuous recording simply is not enough time to accomplish the general goal

of the Track Crawler.

Conclusively, examining the advantages and disadvantages of the current camera systems of up to 3 GoPro® Hero 8 Black cameras is important in developing an underlying foundation in what the criteria need to be in order for a future project to implement a new system. While the scope of this report is not to develop any specific solution, rather than make recommendations for future engineers, these advantages and disadvantages will play a critical role in determining whether or not to use a certain camera or a certain system. These advantages and disadvantages will constantly be referred back to over the course of this report, and any future engineer utilizing this report to implement another system on the Track Crawler Robot should refer back to the advantages and disadvantages of the current system in order to make a well thought out and developed decision on the new imaging system.

Chapter 3 – Characteristics of Videography

The purpose of this chapter will be to give a background of characteristics that are commonly used in the decision-making process of selecting cameras in a videography scenario. In future chapters, these characteristics will be used to outline the reasoning as well as provide the reader with a good idea of what the current camera is good at doing and what it is not.

3.1 Characteristics of Videography

1) Aperture: This is a term that references the opening and closing of a lens's diaphragm in which to let in more or less light. This characteristic is measured in f/stops in a way such that a lower f/stop represents more light entering the lens, or a higher aperture. Aperture is important for the scope of this project considering aperture governs the exposure of an image or video which is a crucial aspect of motion blur, especially when dealing with vibrations. For any future iterations of a new imaging system, the camera lens should be rated in which the aperture is as customizable as possible
2) ISO – Similar to aperture dealing with the level of light in an image, ISO rating is a characteristic that will either brighten or darken a photo by exaggerating the grain, or noise within a video. While this can be ideal for shooting in low light environments, too high of an ISO rating can lead to a very grainy, or noisy, video. The simplest way to understand ISO as it relates to image quality is that doubling the ISO rating of footage, will double the brightness of footage. Contrary to aperture, ISO is a characteristic that changes the metadata within footage rather than the physical characteristic of aperture, therefore, ISO rating should only be changed when the aperture is not able to be changed.
3) Focal Length – Focal length refers to the minimum distance in which a lens can put a subject in focus. For example, the minimum focal length for the GoPro® Hero 8 Black is 12 inches. Therefore, an ideal system would contain a focal length less than or equal to 25% of the previous value, which would put the new minimum focal length at 9 inches.
4) Auto-Focus – Auto-focus refers to a camera's ability to automatically focus on a subject as the distance from the lens changes. Camera's use specialized processors and sensors to continuously determine if a subject is in focus. For the application of this project, it is critical that the new camera design contain auto-focus capabilities since the user will not have the ability to manually adjust the focus.

5) Video/Image Stabilization – Video/Image Stabilization is just like the name implies. This technology stabilizes a video in real time in order to reduce blur. Video stabilization works by slightly zooming in the footage to the viewable area, and imbedded software is able to detect sudden movements in the footage and correct the footage frame by frame. The current image system, comprising of the GoPro® Hero 8 Black, contains its own image stabilization technology, however at the high frequency vibrations that the Track Crawler experiences, the software cannot detect and correct the image.
6) Resolution – A video's resolution refers to the number of pixels that are in a given frame. Resolution plays a key role in the video's image quality in such a way that more pixel's correlates to a smoother higher definition of image.
7) Framerate – Contrapositive to resolution, a video's framerate is the speed at which a camera was able to record video. This characteristic is commonly measured in units of frames per second (FPS). In relating framerate and resolution to each other, they typically operate at the detriment of one another. For example, a camera might have the ability to operate at a high framerate but might only be able to shoot at a lower resolution. On the other hand, typically, a camera that is on a higher resolution setting, is only able to record at a lower framerate. When implementing a new video system into the Track Crawler Robot, both of these characteristics need to be maximized considering they are foundational to providing clear, smooth footage back to the user.

While not a direct characteristic of photography, another foundational criterion that needs to be considered when looking at video systems is cost. Ideally, one would be able to maximize all of the positive aforementioned characteristics in a camera while minimizing cost. However, that is rarely the case. It is important to develop a clear boundary of the goal that is trying to be accomplished by the camera being used and determine where the team can afford to trail in some characteristics and where the team needs to leader in others.

Chapter 4 – Characteristics of Photography in Relation to the Track Crawler Robot

This chapter will take the information from Chapter 3 and relate it to the analysis done on the characteristics needed in relation to the implementation of the new system. In this chapter, we will look at the major similarities between different makes and models of video cameras that meet the qualifications to support significant improvement from the previous video system. In further chapters, the advantages and disadvantages will be summarized further in order to make a well informed recommendation on what video camera should be implemented.

4.1 Canon Models

- Canon EOS 90D (DSLR) ($1,199)

Figure 2: Canon EOS 90D Body (Photo by Canon USA)

Pros	**Cons**
Low Cost	Limited framerate at high resolution
Adequate Resolution/Framerate (1080x120FPS)	Smaller Sensor
Lightweight (approx. 701g)	

- Canon PowerShot G5 X Mark II ($899.99)

Figure 3: Canon PowerShot G6 X Mark II (Photo by Canon USA)

Pros	**Cons**
Very Low Cost	Low Battery Life
Low Volume	No Audio Jack
Wi-Fi Capability	Lackluster Auto Focus

- Canon EOS 800D Rebel T7i ($579.00)

Figure 4: Canon EOS 800D (Photo by Canon USA)

Pros	**Cons**
Reliable Auto-Focus	Discontinued by Canon (May be difficult to obtain)
Superior Image Quality	Video limited to 1080p
Strong Battery Life	Low Dynamic Range

4.2 Nikon Models

- Nikon D7500

Figure 5: Nikon D7500 (Photo by Nikon®)

Pros	Cons
Dedicated Fine-Tuned Auto Focus	Large Volume and Weight
Superior High ISO Performance	Limited information on UI
Strong Battery Life	4K Video is Cropped

4.3 Sony Models

- Sony ZV-1 ($749)

Figure 6: Sony ZV-1 (Photo by Sony Group Corporation)

Pros	Cons
Small by volume and weight	Low Battery Life
High Frame Rate (Up to 960FPS)	Overheating issues in 4K
Affordable Price	Small Sensor

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-

- Sony a6400 ($1,298 w/lens)

Figure 6: Sony ZV-1 (Photo by Sony Group Corporation)

Pros	**Cons**
Compact	Low Battery Life
Superior Autofocus	Limited External Controls
Superior Sensor	Lacking Image Stabilization

- Sony a7 III ($1,998)

Figure 7: Sony ZV-1 (Photo by Sony Group Corporation)

Pros	**Cons**
Good Autofocus Systems	High Cost
Good Battery Life	Overheating issues
5 Axis Stabilization	Lower Quality Sensor

Chapter 5 – Ambient Light Sensor Implementation

As mentioned in the earlier chapters of this project, the implementation of an ambient light sensor onto further iterations of the track crawler robot would aid in the projects ability to capture high quality video. Implementation of a ambient light control system, would be fairly easy, as there are already many available software and control algorithms for such the task, and in this chapter, we will explore the best option available for another iteration of the Track Crawler Robot.

5.1 Arduino Ambient Light Sensor

Arduino currently has a free project available, on its project hub, that is geared towards the creation of an ambient light sensor. This project contains the necessary code, diagrams, as well as bill of materials to create an ambient light sensor applicable to almost all types of projects. In the case of the Track Crawler Robot, one would be able to implement this project with larger, upward facing LED lights. LED lights are ideal for this application because they allow for a variable amount of light to be emitted based on the need, while lasting longer than a traditional incandescent lightbulb, that you might find in a common household environment.

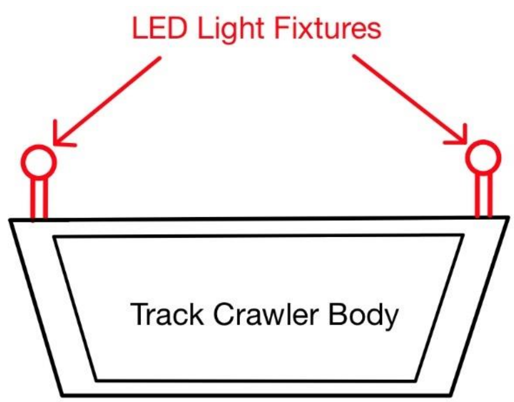

Figure 8: LED Light Location on Track Crawler Robot

In an effort to minimize cost and maximize energy efficient, since the implementation of this system would require power from the Track Crawler's battery, it is recommended that to use no more than 60 Watt rated LED light bulbs for this implementation.

Directly adapted from the project, provided by Arduino, the control system diagram is shown in the following figure:

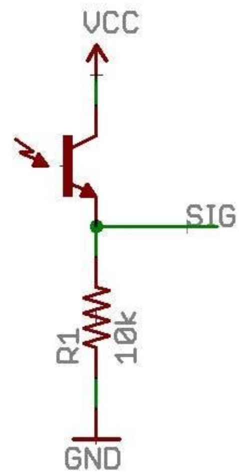

Figure 9: Control Diagram for Ambient Light Sensor Implementation [9]

As common with most sensors, a 10 Ohm resistor would need to be wired to the ground of the circuit, whereas on the other side of the parallel, a voltage change in a photoresistor would generate a signal, in which the program would be able to interpret, and adjust the power applied to the light bulb as necessary. For this application, it would be ideal to utilize a specific "TEMT6000 ambient light sensor", which is a type of photoresistor directly designed for controls systems in ambient light [9]. This system would then be routed through the Arduino Pro Mini 328 Microcontroller by SparkFun®. All in all, the ease of use and implementation of this system makes it ideal for an ambient light sensor that would meet the needs of the Track Crawler project. Needless to say, the overall cost of this system would be less than $20.00, which makes it ideal in the overall goal to maximize efficiency and minimize cost.

Chapter 6 – Infrared Light Camera for Temperature Analysis

6.1 Overview

When using the Track Crawler Robot to examine the underbody of rail cars, in addition to be able to visually investigate the systems within, it is also useful to determine the absolute temperature of the components that the robot is currently examining. In most railcar underbody, many of the components and systems are temperature dynamic, meaning that their temperature is constantly changing, and with the maintenance motivation of the Track Crawler, it would be helpful to view an analyze the absolute temperature of the components the robot is viewing. This chapter will go over the pros and cons of different infrared cameras, similar to Chapter 4, in which we looked at different video cameras. To reiterate, while the scope of this report is not to provide an outline as to what design will proceed, this report is meant to be referenced at the commencement of the next generation of the Track Crawler Robot.

6.2 Infrared (Temperature Detecting) Camera Models

- Klein Tools TI250 Thermal Imager ($297)

Figure 10: Klein Tools TI250 Thermal Imager (Photo by Klein Tools®)

The Klein Tools® TI250 Thermal Imager is a compact infrared camera that has the ability to detect temperatures from 32° F to 113° F. This large range of temperature detection makes it ideal for extreme applications. Combined with its lightweight and compact design, the TI250 allows the user to gain a true understanding of whatever application they are trying to understand.

- FLIR C3-X Compact Thermal Camera ($525)

Figure 10: FLIR C3-X Compact Thermal Camera (Photo by Teledyne FLIR)

One of the major brands in thermal imaging technology is FLIR. For good reason, the C3-X Compact Thermal Camera offers many of the great features of a modern video camera, but with the objective of capturing thermal images. With an detection range of 32° F to 212° F, this device is able to detect a wide range of temperatures with an accuracy of up to 5.5° F. One of the key advantages to the C3-X is its ability to connect to outside hardware via Wi-Fi as well as offering multiple different modes of image. A user can switch between infrared mode and visual mode in order to get a better idea on what they are looking at and why. This camera, coupled with a new video imaging system would, without a doubt, lead to superior results to that of any other.

Chapter 7 – Conclusion and Recommendations

7.1 Overview

As mentioned, multiple times, this report is meant to serve as a foundation for future engineers to refer to when embarking on developing a new iteration of the Track Crawler robot, therefore while the recommendations and conclusions outlined in this chapter are based on significant research, they are designed to be fluid and change as the needs for the project change over time. However, over the course of any new development of the next generation of the Track Crawler Robot, this report, and its conclusions, should be regularly referenced in order to continuously verify the project is fulfilling the needs of its respective stakeholders.

7.2 Recommendations for Implementation

The recommendations in this chapter were based on a total of 3 categories that were conceived based on restraints outlined by the Track Crawler team. These restraints are as follows:

- Camera body should remain under $1,000.00
- To solve the original problem of the current camera system yielding blurred images, the camera should be able to shoot video at least 1080p/120fps
- The Track Crawler's geometry should not have to be altered in order to accommodate space for any new components/systems

Therefore, based on these constraints, the following 3 recommendation categories were developed.

7.2.1 Cost Efficient Recommendation

With one of the major constraints of this project being the cost, it is important to create a recommendation that focuses on the cost of the system in general. Like mentioned in the above constraints, the ideal video camera would remain under $1,000 while maximizing performance as much as possible. The cost effective recommendation is as follows:

Video Camera	Lighting System	Infrared Camera
Canon EOS 800D Rebel T7i	Arduino Ambient Light Sensor	Klein Tools TI250 Thermal Imager

Table 2: Cost Efficient Recommendation Components

With this configuration of hardware, the total cost of the system, including the camera which itself is mean to be under $1,000, would all together total less than $1,000. For a cost effective approach, this configuration is the best path forward.

7.2.2 Maximum Performance Recommendation

Maximizing performance is always the goal of any new iteration of any system. Specifically, in the case of the Track Crawler Robot, the main goal was to solve the problem of blurred video from the locomotion of the robot. This recommendation is based on the system with the best performance to solve the problem to the highest standard. This recommendation is as follows:

Video Camera	Lighting System	Infrared Camera
Sony a7 III	Arduino Ambient Light Sensor	FLIR C3-X Thermal Imaging Camera

Table 3: Maximum Performance Recommendation Components

With the lightweight and powerful nature of the Sony a7 III and the robust design of the FLIR C3-X Thermal Imaging Camera, this series of hardware will maximize performance in any situation the Track Crawler Robot is put under. While not quite adhering to the cost recommendation, these series of hardware provide the most value per dollar spent, which is at the core of this recommendation.

7.2.3 Volume/Ease of Use Recommendation

The third and final recommendation category is based upon the third design principle for the development of the next generation Track Crawler. Being able to seamlessly implement new video, infrared, and lighting hardware onto the robot, without having to change many of the foundation principles was the motivation of this recommendation. This recommendation is as follows:

Video Camera	**Lighting System**	**Infrared Camera**
Sony ZV-1	Arduino Ambient Light Sensor	Klein Tools TI250 Thermal Imager

Table 4: Volume/Ease of Use Recommendation

Based on the volume and beginner friendly nature of these components, they make up the Volume/Ease of use recommendation. While not sacrificing cost or performance, utilization of this design will be the most seamless implementation into the current iteration of the Track Crawler Robot.

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