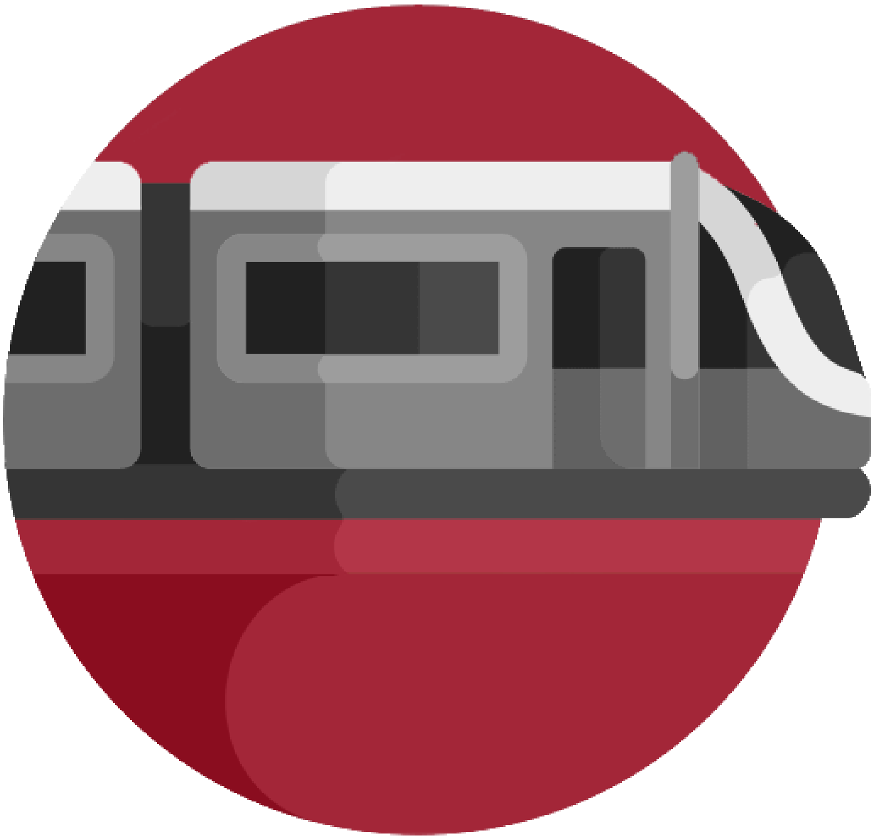
Stevens Institute of Technology
The Innovation University

Phase 1: Senior Design Report
Autonomous Subway Inspection Vehicle

Omar Aziz, Noah Bolzoni, Brandon Castro,
Anthony Lucero, Sean Maggio, Marcin Wisniowski

Advised by: Dr. Kevin Connington



A Proposal and Conceptual Design for an Autonomous Subway Inspection Vehicle

October 8th, 2019

1 Abstract

The New York City subway is by far the busiest metro service in the United States. Annual subway ridership in New York City surpassed 1.68 billion in 2018 and daily passengers exceed 5.6 million [4]. Therefore, each issue found on the subway track inevitably leads to the inconvenience and delay of millions of Americans living in New York City. Even with the current advancements in technology and automation, many railway track inspections are conducted regularly by human inspectors. In order to satisfy current regulations prescribed by the Federal Railroad Administration, a mainline track is usually required to undergo a weekly inspection and a geometry car inspection is not considered acceptable for meeting this required inspection frequency [1]. It becomes apparent, therefore, that inspectors are in high demand and yet low in availability.

The Autonomous Subway Inspection Vehicle (subsequently referred to as the ASIV) looks to increase the productivity of subway inspections by uncovering and flagging warnings for track defects early, in order to concentrate a subway inspector's efforts into distinct geographic areas of focus. While the current regulations may restrict the creation of a fully autonomous system, the project, regardless, adds value by creating an autonomous and live asset management of the subway track. In the future, the system can be used for stronger analysis for proactive instead of reactive operational investments and scheduling of site-technicians and inspectors.

Contents

2 Project Statement

2.1 Motivation

The Tri-State area continues to attract hundreds of thousands of job seekers and tourists who flock to Manhattan and its surrounding boroughs for work and leisure respectively. This poses a major problem for transportation since existing systems are near capacity if not already exceeded, especially in terms of automotive traffic. Thus, public transportation has become the preferred method to travel within the city due to its flexibility and its sustainability, though it too is plagued by delays, cancellations, and other interruptions that decrease commuter confidence in the system. In the case of subways, a portion of said interruptions can be directly or indirectly attributed to the inspection of track infrastructure across the entire system for defects such as misaligned or damaged rail. The primary motivation for designing ASIV was to reduce delays and costs specifically associated with said process. ASIV is envisioned as a self-propelled track inspection robot that can survey track for defects with minimal human oversight. Frequent oversight of the rails by a fleet of cheaply produced ASIV units would ultimately increase the efficiency of the inspection process and improve the safety margins since defects can be pinpointed before they grow into serious issues. Ultimately, this results in a more robust public transportation system that meets the needs of New York City's commuters and visitors.

2.2 Goals and Objectives

The main goal revolves around creating a cheap but effective option to autonomously collect and monitor data on a subway line's rail. A fully-encompassing system is envisioned for the future, but the current focus is on gathering data for track measurements and obstructions and staying away from more generalized measurements that may pertain to tunnel clearances or third rail measurements. If ASIV is accepted as a viable solution, future work may expand on what measurements will be taken. Another aim is to create a system that is non-intrusive to current rail operations and will be able to autonomously remove and place itself onto the rail if objects are identified to be approaching on the rail.

2.3 Major Issues

With current research and background in mind, there are two major issues that prove to be the most challenging. Further review of literature and insights from experts in the field may serve to address these issues.

1. A lack of external data sets to build and test around may stunt design & analysis
   - Many inspection services limit the amount of information they share with the public when it comes to technical data and industry-standard tolerances. Ultimately, a rail network becomes very hard to understand how to recreate when these values are not shared. This will become difficult when choosing between different sensors and choosing which variables to monitor to stay within thresholds. An in-depth review of available capital investment documents and dialogue with industry employees will be helpful in acquiring this type of information.
   - Since ASIV is an autonomous system that is non-intrusive to the trains that run alongside it, an issue arises with the need to have a fast retraction method for the device. It will be crucial to incorporate sensors that can detect an approaching train to give ASIV the necessary time to retract off the rails.
2. It will be challenging to test the system and evaluate whether it fits under industry protocols.
   - It is understood that testing with a trial and error type of approach is not possible in this situation to help hone on specific values as testing on physical track will be limited unless a contact can be found. Instead, reliance should be placed on literature review and current practices for thresholds and sensor data, and reasonable assumptions should be made before testing and making improvements.
   - It is unknown if a company will be willing to supply rail for the purpose of testing. Alternatively, it may be necessary to build a small section of track, with known defects, and test the ASIV across this instead. Nearby areas can also be surveyed to determine if any inactive right-of-ways have useable tracks.

- Given testing will be difficult to conduct, sensors will need to be bought knowing that it is a likely candidate for use.
- It will become a necessity to learn how to create a data collection GUI for front end users to monitor and see issues that have been flagged.

3 Literature Review

3.1 State of the Art Technology

The Metropolitan Track Authority (MTA) currently employs the use of 4 independent subway cars outfitted with advanced sensors and imaging equipment to inspect over 673 miles of subway track in New York City. According to the MTA, these high-tech train cars, also known as 'track geometry cars', measure the following track parameters and more [3]:

- *Longitudinal profile of both running rails* - the angle/heading of the rails with respect to each other
- *Horizontal alignment of both running rails* - both rails are respectively level
- *Track gauge* - distance between the rails (Standard gauge, 1435mm)
- *Tunnel and platform clearances*
- *Corrugation of running rail surface* - repeated patterns of wear and tear/deformation
- *Third rail height and gauge* - height and distance to the powered rail from the nearest running rail
- *Vertical gap between the top of the third rail and the protective board*
- *Internal rail flaws*
- *Track grade* - inclination

Track geometry cars are equipped with high-frequency laser scanners, high-resolution cameras, ultrasonic sensors, thermal images, and various other high-end electronic, mechanical, inertial, and laser equipment [3]. This is accompanied by computers that can analyze the data in real time as the car is moving up to 50 mph.

A very advanced system like this provides a comprehensive and valuable analysis of the state of the tracks, but it is also very expensive to purchase, operate, and maintain. The newer cars cost $2.5 million each. They are often manned by around 6 engineers/maintenance crew, and contain many subsystems that must be maintained to remain operating at high accuracy. Additionally. the limited number of these track geometry cars means the tracks can only be inspected around 6 times a year.

Another interesting method that has been explored was inspection via machine learning. Graduates at the University of Central Florida studied the potential of inspecting track via cameras mounted on a hi-rail truck [2]. Imagery from these cameras was examined by purpose-made software to detect defects with specific algorithms applied for each case. As with conventional track geometry cars, the tested hi-rail equipment also employed accurate laser sensors to measure the gauge of the rail. In the case of this measurement, the data could be plotted in real time via a LabView interface with respect to distance traveled. While, field testing the machine learning functions produced inconsistent results, the conventional laser sensors proved to be satisfactory. However, given that the report was published over eight years ago, the plausibility of incorporating machine learning could be given future consideration given the recent interest in this and similar technologies.

4 Needs and Specifications

4.1 Societal Needs

The proposed design for the track inspection vehicle aims to make mass transit by train much more efficient and safe. Current subway transit is constantly plagued by delays and interruptions in service due to issues caused by the track. The four large track inspection vehicles that the MTA presently uses, are only able to inspect the full length of the track 6 times a year. This means that there are two months in between inspections. This gap in between inspections allows for potential deformation and breakage to go unchecked for up to two months. During this time the defects could cause derailments and therefore inconvenience the public. The proposed design aims to make more frequent inspections so that more defects can be identified. With more inspections, there will be a reduced number of derailments and inconveniences to the public.

4.2 Customer Needs

The main intended customer for the track inspection vehicle would be the MTA or Path as they are directly responsible for transportation by subway. The MTA/Path requires for an inspection vehicle to take reliable measurements, save space, and to save time. As stated before, the MTA only has four track geometry cars that are able to inspect the full length of the subway system a mere six times a year. These cars are full sized subway cars that are fitted with sensors and computers with people inside to inspect the tracks. For the MTA/Path to increase efficiency, a smaller, more cost effective solution is needed. With the risk of derailments and deformations, the MTA needs a quicker and cheaper way to inspect tracks. By having a machine that has accurate sensors, the inspection vehicle will be able to safely determine if a rail is aligned and that all rails are up to code. A smaller vehicle will also save space as well as reduce the costs of use as having an autonomous vehicle will help measure the rails quicker and require less personnel for operations.

5 Concept Generation/Selection

5.1 Concept Exploration

Initially, four general concept categories were created to begin the selection process. These concepts were general ideas of the overall function of the device. The device was determined to operate in four ways - autonomously as a vehicle that navigates the tracks independently, a sensor module mounted to the bottom or sides of passenger train cars, a module coupled to the front or rear of a train car that runs on the tracks, and sensor modules that are fixed near the track itself. A list of pros/cons for each category was constructed below:

Pros	Cons
• Does not require any modifications to any existing infrastructure or rolling stock • No initial assembly or construction required • Once parameters input, robot does not need an operator or constant supervision • This is a novel solution - nothing similar exists in market	• Occupies track and works best during down-times in service • May require training to use interface and input parameters • Requires moving parts such as motors

Table 1: Concept A: Autonomous Mobile Robot

Pros	Cons
• Will not impact operations • Does not require moving parts • No supervision required	• May require modifications to rolling stock to accommodate mounting • Many similar solutions already exist in market • Some assembly is required

Table 2: Concept B: Car-Mounted Sensor Module

Pros	Cons
• Theoretically simple to design • Relatively novel solution	• May obstruct coupling to other equipment • Requires wheels and other moving parts • May require modification of rolling stock to accommodate coupling to device

Table 3: Concept C: Sensor Cart Pushed/Pulled by Existing Subway Equipment

Pros	Cons
• Once installed, there will be no impact to regular operations • If data is uploaded directly to engineering department directory, it will be very easy to use • No moving parts required	• Very expensive to install solution system-wide • Complex and long assembly and roll out process

Table 4: Concept D: Arrays of Stationary Sensors Monitoring Tracks for Defects

To facilitate the selection process, a selection matrix was created to rank the 4 categories of concepts and decide which of those to proceed with. Each category was ranked based on a relevant set of selection criteria. After scoring each category in each criteria, the scores were added and the concept categories were ranked. The top two concepts were chosen to move on in the selection process. As shown below, the autonomous and car-mounted categories were chosen.

Methods of Operation for Inspection System

Selection Criteria	Autonomous	Car-Mounted	Car-Pulled	Stationary
Requires System Modification	+	0	0	0
Ease of Use	0	+	0	+
Installation	+	-	0	-
Impact on Operations	0	+	-	+
Low Cost	+	+	+	-
Moving Parts	-	+	-	+
Unique	+	-	+	0
Net Score	3	2	0	1
Continue?	Yes	Yes	No	No

Table 5: Selection of Inspection System

Next, the two concept categories were compared again. This time, weighting for the criteria was used that was relevant to the two concept categories. The autonomous concept was chosen from this scoring system.

Design		Autonomous		Car-Mounted	
Selection Criteria	Weight	Rating (1- 5)	Weighted Score	Rating (1 - 5)	Weighted Score
Impact on Operations	25.00%	3	0.75	5	1.25
Low Cost	25.00%	4	0.8	3	0.6
Requires System Modification	15.00%	5	0.75	3	0.45
Ease of Use	15.00%	3	0.45	3	0.45
Installation	15.00%	5	0.75	1	0.15
Moving Parts	5.00%	2	0.1	4	0.2
Unique	5.00%	5	0.25	1	0.05
	Total Score	3.85		3.15	
	Rank	1		2	
	Continue	**Yes**		**No**	

Table 6: Final Weighted Selection of Inspection System

6 Further Concept Generation

An autonomous vehicle has two main functions

1. Measuring the tracks
   - What items will be measured?
   - Tools for measurement
2. Evading Trains
   - Trigger Method
   - Physical Design

6.1 Measurement

It is too complex and costly to match the number of measurements made by more advanced track geometry cars. ASIV should focus on collecting the most crucial measurements effectively. Investigation led to considering a few key measurements. More research will be done in the future to see if other measurements are crucial to preventing derailment, but ASIV is intended not to measure all rail geometry, but only what is needed on a more frequent basis. This ensures a more competitive price, and in our limited time frame, a more quality system.

Key Measurements:

- Track Gauge: In an interview with a representative from the train operations department of MTA, the interviewee was asked, “What is the most important track geometry measurement?” The response was to “definitely measure track gauge,” as improper gauge can cause derailment. Track gauge is the horizontal distance between the tracks.
- Track Profile: To turn, the flange of the car wheel rubs against the track. If the track is worn down, the wheels can climb its way out of the rails. Track profile is the cross sectional shape of the rails, and is thus an important measurement to monitor.

Other items that may be feasible and may have a significant level of importance are cant (angle right or left relative to direction of travel) and curvature [15].

6.1.1 How to Measure

In an autonomous context, machines use sensors to measure.There are sensors which measure proximity and distance. Proximity sensors give a binary output and are meant to indicate if something is present or not present. Distance sensors return numbers of distance measurements.

Distance sensors are divided into two main categories below: contact and non contact. Within each category are various sensors and descriptions of their technology. This is a list of potential candidates for ASIV; a list of sensors to avoid follows.

1. Contact
    - Linear Variable Inductive Transducer (LVIT) and Linear Variable Differential Transformer (LVDT) sensors are used to measure linear distance. LVIT contains a rod which moves relative to a circuit in a housing, and the position of the rod can be measured with the circuit [11]. More research must be done to see which is better and differentiate the two. There are models with return springs, and this would be useful as a sensor that runs along the rails using a roller. They have variable stroke lengths, and are inexpensive [10] [9] [6] [13].
    - A linear potentiometer may be viable as a touch sensor, and strain based sensors will be searched for next.
2. Non-Contact
    - Most of the sensors found are non-contact. Inductive sensors create an oscillating magnetic field using an oscillating circuit. This field induces eddy current in nearby metal which creates magnetic fields which oppose the field created by the circuit. This change in magnetic field can be read by the circuit and a distance is calculated. These sensors have ranges from a few millimeters to a few centimeters. They can only detect metal [6].
    - Capacitive sensors are an open capacitor configuration. Approaching objects act as a changing dielectric in the capacitor and allow for an oscillating current to flow. This current helps indicate the sensor's distance from the object. They have similar distance capabilities to inductive sensors [6].
    - Laser sensors are a type of photoelectric sensor which measures distance by analyzing reflected light. They can take the form of 1D measurement, 2D profile measurement, and 360deg plane mapping. These are more expensive than inductive or capacitive sensors [7].
    - There are other types of photoelectric sensors, including one as low as $10, but it is unclear if it relies on lasers and only measures down to 2 cm [7]. Some others use LEDs, but more research must be done to identify cheaper laser sensors or alternative types of photoelectric sensors [14].
    - Ultrasonic sensors use reflected sound to detect objects' distance. They can measure approaching and receding objects but it is unclear if they can measure transversely moving objects. Keyence says that among their products, ultrasonic sensors have a slower response time to optical sensors [5] [12]. More research is needed on this type of sensor.
3. Sensors to Avoid
    - Confocal chromatic sensors split a beam of white light into chromatic parts. Depending on the distance to the object, a different wavelength of light is reflected back to the sensor [8]. These are presented as solutions for super high resolution (small measuring width), small distance, high precision measurements. Examples include electronic circuit boards [8] [12]. A large box also appears to be required to interpret the data. This is likely not good for our application to to its high price and intended uses.
    - Some photoelectric sensors can use infrared light, but ASIV this is also a product of heat, and ASIV works in an environment with constantly changing temperatures which will disrupt sensor operation.
    - Magneto-inductive sensors and certain contactless LVITs require the measured object to have a magnet attached to it. Our machine is constantly moving, so this is impractical.
    - LVITs that need to attach to the measured object are logically impossible.
    - Lidar is a laser based mapping system. It is too expensive and meant for more advanced surface mapping [16].

- Points to Consider when selecting a sensor:
  - Minimum and maximum measurement distance
  - Accuracy of the sensor
  - Price of the sensor
  - Resolution of the sensor
  - Resilience towards the working environment (dust, vibrational, electrical noise resistances)

Companies to consider when purchasing sensors		
• Omron • Digikey Electronics • Novotechnik	• Micro-Epsilon • Keyence • Alliance Sensors Group	• Baumer • TE Connectivity • IFM

Table 7: Sensor Companies to Consider

In the future, a more in depth analysis will be made between sensors, accounting for cost, size, power draw, accuracy, etc. We will also see if low cost image recognition exists, since we plan to have cameras on the device for operators to use. Possible sensor locations include the following:

- Guides that run along the rail and have sensors pointing inwards that measure the distance between each other for gauge measurements
- Sensors that measure distance from the chassis to the rails for gauge measurements
- Sensors which extend beyond the chassis to allow curvature measurements
- Multiple small sensors to measure profile mounted to chassis
- Specialized sensors made to measure profile mounted to chassis

6.2 Evasion

6.2.1 Triggering Evasion

Triggering evasion can be done using a mechanical/electrical or computational (sensors and a computer) trip. A mechanical or electrical trip would entail an approaching train causes the vehicle to leave the tracks through a simple direct action. For example, the train could tread on an apparatus trailing ASIV or bump into a button on ASIV's chassis, inducing an electromagnetic coil to shut off and allow ASIV to fall via a folding mechanism. In a computational situation, all action is routes to a computer, which then directs the removal from the track. Using a computer allows for more advanced detection, and is thus a better option.

A remote beacon placed at the start point could be used to send a frequency that shuts off an electromagnet or similar apparatus, but a computer allows for more advanced signal detection and reduces the amount of erroneous signal responses that could occur. It also allows re-positioning onto the track to be a much less complex task. One could suggest using the electrical signaling system in the subway for advanced warning, but this could lead to altering the signal system, would not provide very advanced warning at the beginning of "signal blocks" (sections of track in which a train can be detected), and would not be viable if the subway signal system is upgraded. Sensors and computational chips are a simpler, more flexible option.

Vibration sensors are a possible means of detection, but may be triggered by ASIV's own movement. Proximity sensors or cameras could be placed at the start point of ASIV's deployment and send a warning signal to ASIV to retract. ASIV could then return to the rails via an operator's signal, or autonomously. It could have proximity sensors or vibration sensors onboard to determine if returning to the rails is safe. More research must be conducted to determine how ASIV would detect trains, and then detect the absence of trains.

6.2.2 Physical Design

Initial ideas for an autonomous vehicle became new concepts of their own. The most prevalent issues for an autonomous vehicle was the frequent passing of trains. This places constraints on the conceptualization process. The vehicle had to be very low profile. It also needed a way to reliably and safely evacuate the track when a train is detected coming towards it. To perform this function, the wheels must be able to quickly retract to a narrower profile as a train is approaching. It must also have some sort of mechanism that supports the vehicle on the ground as the wheels are retracted from the track. From here, two concepts for these mechanisms were created.

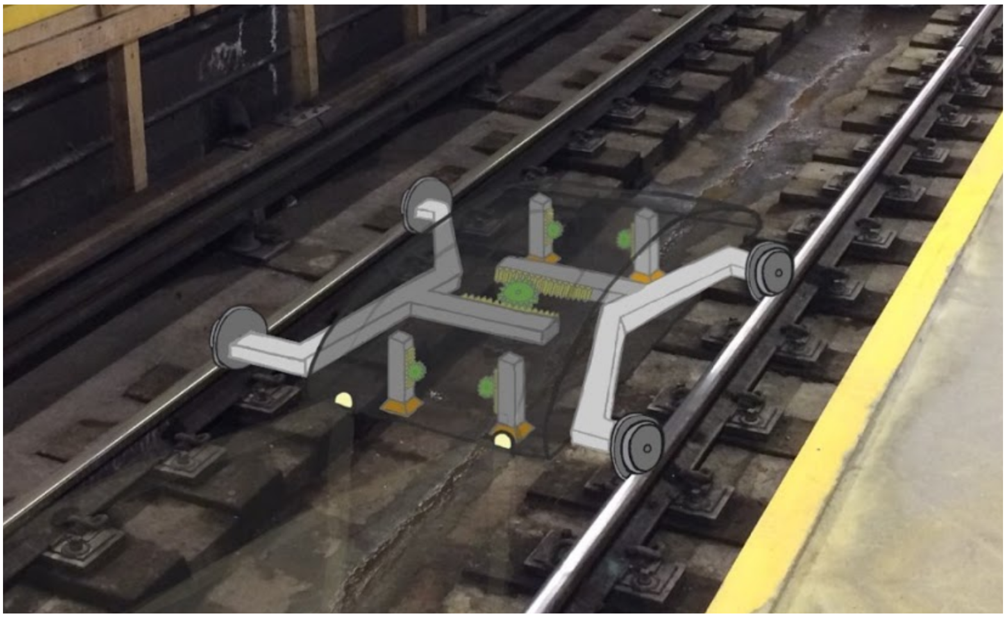


Figure 1: Horizontal Retraction Concept

The first concept relies on rack-and-pinions to produce horizontal and vertical linear motion. The horizontal motion is utilized for retracting and extending the two wheel bases on either side. The vertical motion raises and lowers four independent 'landing legs' under the base of the vehicle.

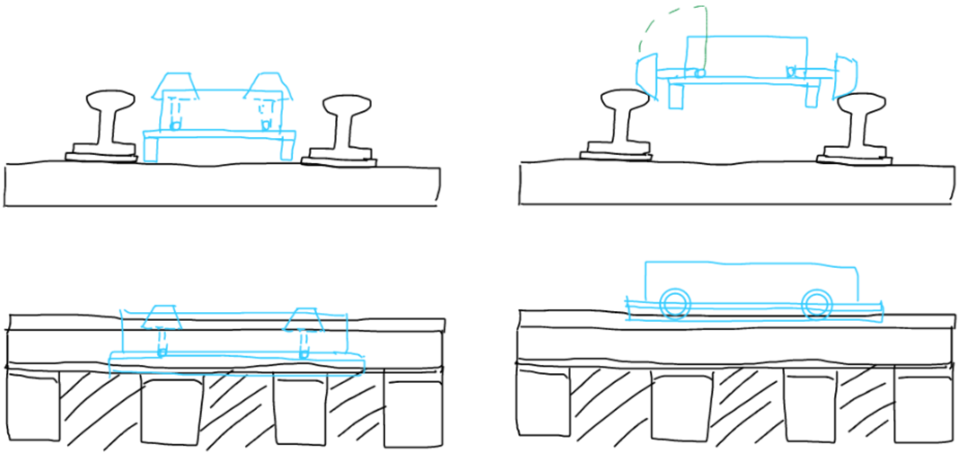


Figure 2: Rotating Retraction Concept

The second concept is a similar approach, but instead of linear motion to retract the wheels, the wheels would be rotated upwards from the track. A similar idea of landing legs was employed in this concept as well.

The two concepts were compared based on a variety of issues. For the first concept, issues arise in the holding torque of the landing leg motors, which would most likely need a locking or ratcheting mechanism to reduce stress on the motors. The second concept had a similar issue of the holding torque of the motors that fold the wheels. If there is no locking mechanism, they would have to support the weight of the entire vehicle constantly, which would require too much power. They also have to be strong enough to lift what will most likely be stainless steel wheels. Assuming a worst case scenario of four independent legs and four independent wheels, the second concept would need an additional 4 motors just to fold in the wheels, making a total of 12 motors. Considering the budget of $700, this is not feasible. Finally, the safety issue of raising the wheels and increasing the envelope of the vehicle to a point where it now comes closer to a passing train is too much of a risk for this concept to be further considered. Since the first concept simply retracts the wheels horizontally, this was seen as the safer option to further iterate upon.

The issue of constantly providing torque in the absence of locking mechanisms that add to the potential failure points has started a search for other solutions to produce the horizontal and vertical motions needed. For this, a linear actuator currently seems to be the best fit. Linear actuators that use ACME threaded rods have self locking capabilities that are able to hold a load unpowered. They provide a stroke length that is more than enough for the avoidance maneuvers necessary for this vehicle, and fit in a fairly compact package. They are not much more expensive than the high-torque motors they would be replacing, and considering that all the motion in the proposed concept was linear, they would also be more efficient in producing that motion, as opposed to a rack-and-pinion system. From here, the use of CAD was employed to simulate the mechanism needed to retract the wheels using three different options.

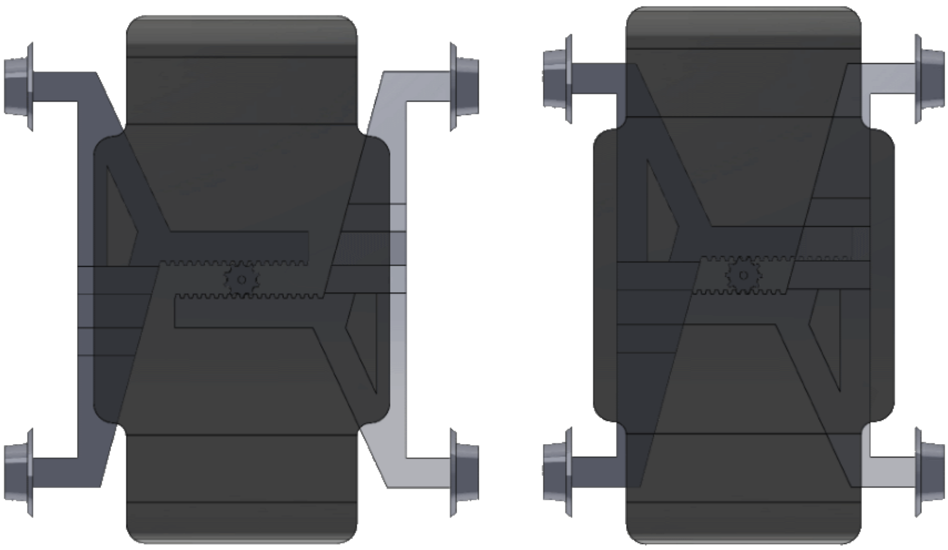


Figure 3: CAD Design Rack-and-Pinion

The first option considered was the initial rack-and-pinion system. The extended and retracted positions are shown above. The racks reside on two identical wheel bases that are in alternate orientations to each other. The pinion is mounted to a motor on the bottom of the chassis, where it sits centered in the vehicle. This option seems to leave much more room in the chassis for other critical components, such as batteries. However, there are weight distribution issues due to the asymmetry of the design. This was discovered through performing a motion analysis in SolidWorks. When placed on a track and beginning the retraction process, the bottom left and top right wheels as shown above did not leave the track. The vehicle instead pivoted along those two points. This is due to the increased weight on those wheels, thus creating more friction. The slots in the wheel bases for the rack arms to go through contribute to much of this weight, and this needs to be revised in the future if this system is selected.

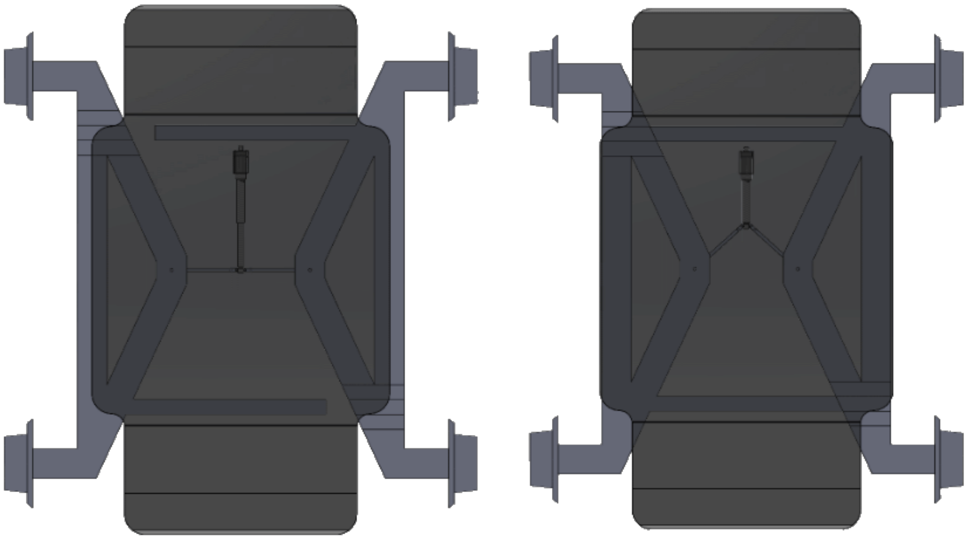


Figure 4: CAD Design Linear Actuator

The next option utilized a single linear actuator to retract both wheel bases that are mechanically linked to each other. The actuator pulls and pushes the joint between the two links to produce symmetrical linear motion on each wheel base. At full extension, the links are in a toggle position, meaning sideways forces from the wheel would not be able to alter the position on the links or the extension of the wheel bases. This may be stable but it might also produce large moments on the actuator rod while it is fully extended. This option is cheaper but relies on a weaker actuation mechanism. With a 6 inch stroke actuator, it does not produce enough linear motion to fully retract the wheels off of the track in the current design. A larger stroke would be needed to produce the desired effect.

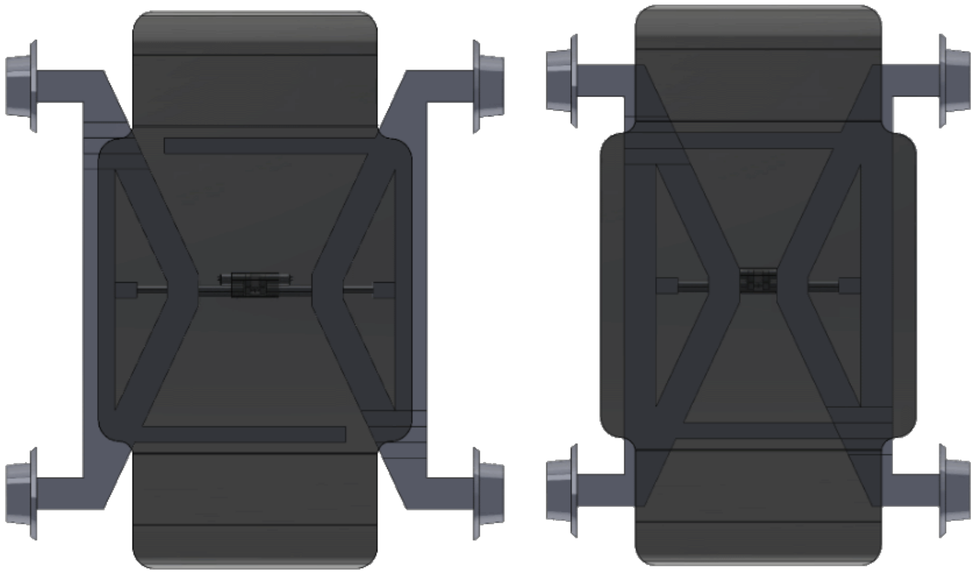


Figure 5: CAD Design Dual-Linear Actuators

The third and final option was to use two linear actuators directly connected to the wheel bases in the same line of motion. While this was more expensive, it was the simplest and provided the largest range of motion of the wheel base (excluding the rack-and-pinion system), at almost 12 inches of retraction total. This will be developed further to see if it is feasible, but it will most likely be the concept to move forward with. An isometric view showing the same concept on rails is shown below.

Landing legs were not modeled in these concepts, but they would most likely also use linear actuators

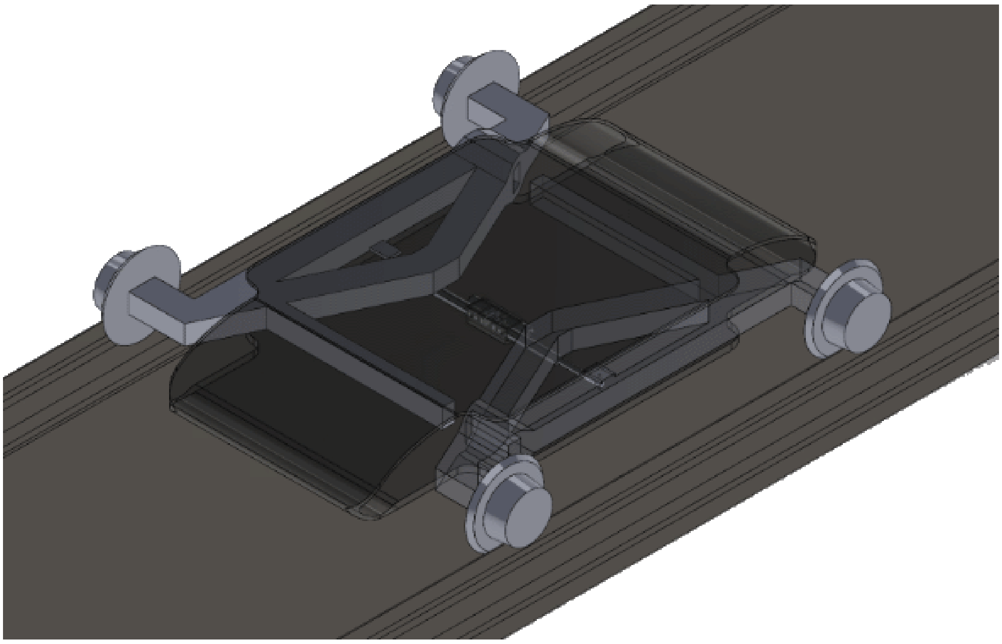


Figure 6: CAD Isometric View

due to the unpowered holding torque that would be able to hold the weight of the vehicle indefinitely until it is safe to get back onto the tracks. Due to the complexity of the surface between the tracks, it would be ideal to have 4 independent actuating legs each equipped with a proximity or pressure sensor to account for differences in elevation under each leg. Two skids, akin to a helicopter or skis, were also considered as a leg design, but it is uncertain that they will be stable on all types of surfaces encountered in the subway environment. Ideally, the four legs would each know how far they have contracted/extended to stabilize the vehicle, and simply perform the opposite procedure to get back onto the track.

6.2.3 General Operation Decisions

With a basic design in mind, the next steps are to decide what functions and equipment will be incorporated into the vehicle. For propulsion, the vehicle will have four independent motors directly driving each wheel. Because of the moving wheel bases, it seems unfeasible to create anything in terms of a drivetrain or incorporate any type of axles connecting pairs of wheels.

For power, use of batteries seems most appropriate for a vehicle that must disengage from the tracks periodically. A third rail solution is too complex to approach for the scope of this project, especially considering the size of transformer required to step down 600 Volts to a more manageable 12-24 Volts. However, there is limited space for batteries, so to ensure the vehicle does not run out of charge on the tracks, an idea for a small infrastructure upgrade was conceptualized. This would entail creating charging stations in empty areas between the tracks, tapping into the existing third rail power lines. The vehicle would disengage from the tracks at known positions where a charging station would be located, and charge until it has enough battery power to continue at least to the next charging station. Preferably, the charging method would be through the use of an inductive charging coil, which can be insulated from the elements. This still requires further analysis, as it is not the main focus of the project.

The vehicle will have an onboard computer/microcontroller that will be constantly logging data to memory. This includes positional data, speed, track gauge, longitudinal profile, horizontal alignment, and rail profile. Some of the sensing analysis is discussed in the next section, but this is still a topic being actively researched. The limitations of what equipment can be included is dependent largely on cost and design, the former of which took a considerable amount of time narrowing down. A preliminary flow of operations is depicted on the next page.

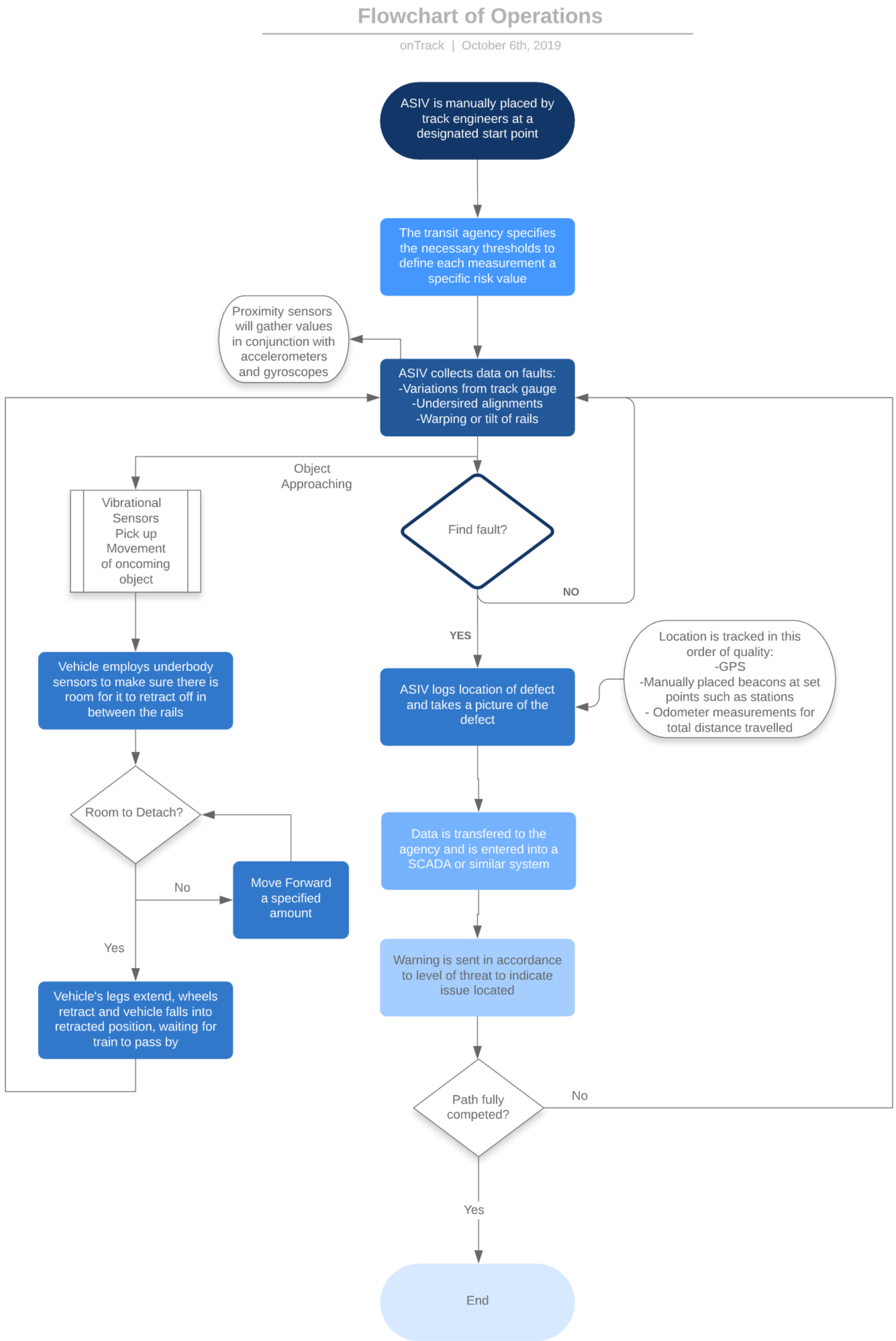


Figure 7: Flowchart of Operations

7 Technical Analysis

7.1 Power Calculations

ASIV's microcontroller, sensors, and DC motors will be powered by an onboard battery. Thus, to determine the required specifications for the battery, calculations will need to be performed to find the power consumption for each component. For the electronics such as sensors and the microcontroller, power can be obtained from the following relation:

$$P = IV \tag{1}$$

Thus, each electrical component's power consumption depends on the current and voltage passing through it. The previous equation can be rewritten in terms of resistance of the component as follows:

$$P = I^2 R \tag{2}$$

The DC motors will likely draw the most power due to the considerable amount of energy necessary to accelerate ASIV and keep it in motion. This power draw can be expressed in terms of the stall torque of the motor and its angular speed.

$$P = -\frac{\tau_s}{\omega_n}\omega^2 + \tau_s \omega \tag{3}$$

Note that this power value is not necessarily constant since ASIV must be capable of acceleration and deceleration, as well as maintaining speed when travelling uphill or downhill.

7.2 Braking Force

There are a number of factors to consider when calculating forces associated with slowing down or stopping ASIV. As with any mass, the kinetic energy of the object must be overcome to decelerate it. Additionally, there is potential energy that must be accounted for when travelling downhill:

$$E_{total} = \frac{1}{2}mv^2 + mgh \tag{4}$$

In terms of forces, the only one present will be that of the brakes pressing onto the wheels. However, one must recall that this braking force will only be effective as long as the wheels do not slip on the rails. Thus, one must consider the coefficient of friction between the rails as they will limit the amount of effective braking force available. In any case, the maximum braking force that can be applied without slipping can be derived as the following:

$$F_{b,max} = \mu mg \tag{5}$$

In this case, m refers to the mass of the vehicle and μ refers to the wheel/rail adhesion coefficient. Thus, one can find the stopping distance d by equating the total energy of the system to the work done by the brakes from equations 4 and 5 above:

$$W_{brakes} = F_b d = \frac{1}{2}mv^2 + mgh \tag{6}$$

$$d = \frac{\frac{1}{2}mv^2 + mgh}{\mu mg} \tag{7}$$

7.3 Calculations Associated with Data Readings

Formulas and algorithms will need to be developed to account for some readings that will not necessarily be given as a direct relation to the inspection values that are needed. For example, with proximity sensors or laser sensors, gauge will be likely be calculated by taking distance values from two sensors and accounting for the location of each sensor with respect to the chassis:

$$Gauge = D_{left} + D_{spacing} + D_{right} \tag{8}$$

In this case D_{left} and D_{right} refer to the distance measurements from the sensor to the rail heads while $D_{spacing}$ refers to the space between each sensor fixed to the chassis.

Additionally, it will be necessary to process data from inclinometers or gyroscopes which will give outputs of angle that will need to be converted to useful values of curvature, alignment, and cross level. These will be determined once a more clear understanding of the sensors to be utilized is attained.

Another consideration to examine is the error in ASIV's measurements such as that in location tracking. An odometer may include some level of error due to wheel slip which will usually result in a higher displacement value than the actual linear value. In this case, it may be beneficial to consider an upper bound for both rotational acceleration and rotational deceleration so that the odometer reading can be corrected for those spurious values.

8 Project Plan

Deliverable	Description
• CAD Model of ASIV	A model of the device will be produced in SolidWorks to verify sizing constraints on rails, placement of components, and simulated operation of the retraction mechanism
• Physical Prototype of ASIV	All necessary components such as chassis, motors, and sensors will need to be procured and assembled as a full-scale prototype for proof of concept.
• Defect Testing Data and Overall Functionality Tests	Tests will be performed to gauge the effectiveness of the onboard sensors and microcontroller. Standard gauge track will be used to find typical defects. Additionally, the self-propulsion system and retraction system will need to be tested.
• Analysis and Recommendation	Data and results taken from tests will be analyzed and used to provide a recommendation on whether to continue based on those findings.

Table 8: Concept B: Car-Mounted Sensor Module

Figures 8 through 10 illustrate the tasks and milestones that must be met to conform to the schedule prescribed by the Senior Design timeline. Any revisions to tasks or their timings will be incorporated as updates to the gantt chart.

	Ta: Mc	Task Name	Duration	Start	Finish	Prede	Resource Names
		Phase 1	**66 days?**	**Wed 9/11/19**	**Wed 12/11/19**		
		Phase 1 Report	**12 days**	**Mon 9/23/19**	**Tue 10/8/19**		**All Members**
		Preliminary Report Due to Connington	1 day	Fri 10/4/19	Fri 10/4/19		All Members
		Phase 1 Presentation	**14 days?**	**Mon 9/23/19**	**Thu 10/10/19**		**All Members**
		Preliminary Presentation Due to Connington	1 day	Wed 10/9/19	Wed 10/9/19		All Members
		Meet with Technical Advisor	**66 days**	**Wed 9/11/19**	**Wed 12/11/19**		**All Members**
		Initial Meeting	1 day	Wed 9/11/19	Wed 9/11/19		Anthony,Brando
		Weekly Meeting	**66 days**	**Wed 9/11/19**	**Wed 12/11/19**		**All Members**
		Initial Research	**16 days?**	**Wed 9/11/19**	**Wed 10/2/19**		**All Members**
		Research concept designs/existing designs	6 days	Wed 9/11/19	Wed 9/18/19		All Members
		Research variables to measure	6 days	Wed 9/18/19	Wed 9/25/19		All Members
		Sensor Research	6 days	Wed 9/25/19	Wed 10/2/19		All Members

Figure 8: Tentative Project Timeline (1)

Develop Project Statement	**6 days**	**Wed 9/25/19**	**Wed 10/2/19**	**All Members**
Establish problem statement	6 days	Wed 9/25/19	Wed 10/2/19	All Members
Define motivation	6 days	Wed 9/25/19	Wed 10/2/19	All Members
Define Objectives/Goals	6 days	Wed 9/25/19	Wed 10/2/19	All Members
Determine Stakeholders/Customer	**14 days**	**Fri 9/13/19**	**Wed 10/2/19**	**All Members**
Gather feedback from Stakeholders and Customers	5 days	Fri 9/13/19	Thu 9/19/19	All Members
Assess Customer Needs	5 days	Fri 9/13/19	Thu 9/19/19	All Members
Prioritize Needs	5 days	Fri 9/13/19	Thu 9/19/19	All Members
Develop Metrics	5 days	Fri 9/13/19	Thu 9/19/19	All Members

Figure 9: Tentative Project Timeline (2)

Final Design Selection	**6 days**	**Wed 9/25/19**	**Wed 10/2/19**	**All Members**
Compare Concepts	6 days	Wed 9/25/19	Wed 10/2/19	All Members
Prioritize measurable variables	6 days	Wed 9/25/19	Wed 10/2/19	All Members
Choose final design	6 days	Wed 9/25/19	Wed 10/2/19	All Members
Phase 2	**26 days**	**Thu 10/10/1**	**Thu 11/14/1**	**All Members**
Phase 2 Presentation	26 days	Thu 10/10/1	Thu 11/14/1	All Members
Phase 3	**70 days**	**Wed 9/11/1**	**Tue 12/17/1**	**All Members**
Phase 3 Report	21 days	Thu 11/14/1	Thu 12/12/1	All Members
Phase 3 Presentation	24 days	Thu 11/14/1	Tue 12/17/1	All Members

Figure 10: Tentative Project Timeline (3)

The table below shows the tentative breakdown of budget allocation for the project. As the project continues these numbers will be reevaluated accordingly.

Item:	Allocation:
Sensors	\$200
3D Printed Parts	\$150
Housing	\$150
Drivetrain Parts	\$200
Total	\$700

Table 9: Current Budget Allocation Estimates

9 Discussions/Conclusions

Significant progress has been made towards finalizing a concept that can be further refined and analyzed. However, progress still needs to be made towards picking the sensors that would be best suited for the functions of the vehicle. A thorough design needs to be completed as soon as possible in order to pursue potential sponsorship opportunities or other kinds of support, such as information/resources on track operations. This is essential to the success of the project, given the limited budget and limited information on critical metrics that need to be considered.

References

[1] Federal Railroad Administration. Track and rail and infrastructure integrity compliance manual. https://www.fra.dot.gov/Elib/Document/16973, 2017.

[2] Esther Resendiz; John M. Hart; Narendra Ahuja. Automated visual inspection of railroad tracks. https://ieeexplore.ieee.org/document/6419832, 2012.

[3] Metropolitan Transportation Authority. New york city transit's wonder train car. http://www.mta.info/news/2012/10/30/new-york-city-transits-wonder-train-car, 2012.

[4] Metropolitan Transportation Authority. MTA annual subway ridership facts and figures. http://web.mta.info/nyct/facts/ridership/ridership_sub_annual.htm, 2018.

[5] Migatron Corp. Precisely measure distances with ultrasonic sensors. https://www.migatron.com/distance-measurement-sensors/, 2019.

[6] Machine Design. Proximity sensors compared. https://www.machinedesign.com/sensors/proximity-sensors-compared-inductive-capacitive-photoelectric-and-ultrasonic#menu, 2018.

[7] DigiKey. Optical sensors. https://www.digikey.com/products/en/sensors-transducers/optical-sensors-distance-measuring/542?utm_adgroup=Sensors%20&%20Transducers, 2018.

[8] Micro Epsilon. Displacement position sensors. https://www.micro-epsilon.com/displacement-position-sensors/, 2019.

[9] Alliance Sensors Group. Lvit technology. http://alliancesensors.com/lvit-technology-what-it-and-where-does-it-fit-sensor-world, 2019.

[10] Harold G. Schaevitz Industries. Lvdt, lvit, and potentiometer comparisons. https://www.hgsind.com/blog/lvdt-lvit-or-potentiometer-comparison-chart, 2018.

[11] Harold G. Schaevitz Industries. Lvit technology and applications. https://www.youtube.com/watch?v=TTLNAaYplH4, 2018.

[12] Keyence. Comparison between ultrasonic and optical sensors. https://www.keyence.com/ss/products/sensor/sensorbasics/ultrasonic/comparison/index.jsp, 2019.

[13] Novotechnik. Position sensor types. https://www.novotechnik.com/Linear-Overview/linear-overview.html, 2019.

[14] Omron. Manual for led displacement sensor z4w-v. https://www.limasoft.cz/omron/pdf/z4wv.pdf, 2019.

[15] Fatjon Seraj. Train track gauge and cant. https://www.researchgate.net/figure/Train-track-gauge-and-cant_fig1_316686329, 2017.

[16] National Ocean Service. High-precision laser measurement sensor. https://oceanservice.noaa.gov/facts/lidar.html, 2019.

List of Tables

List of Figures