



VERMONT

AGENCY OF TRANSPORTATION

# HYDRAULIC INSPECTION VEHICLE EXPLORER (HIVE) CULVERT UPGRADE

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## List of Abbreviations and Acronyms

|        |                                                 |
|--------|-------------------------------------------------|
| AP     | Access Point                                    |
| AR     | Augmented Reality                               |
| DDR    | Differential Drive Robot                        |
| EMF    | Electromotive Force                             |
| FPV    | First Person View                               |
| GPR    | Ground Penetrating Radar                        |
| GTG    | Go to Goal                                      |
| GUI    | Graphical User Interface                        |
| HDPE   | High-Density Polyethylene                       |
| HIVE   | Hydraulic Inspection Vehicle Explorer           |
| IDE    | Integrated Development Environment              |
| IQR    | Interquartile Range                             |
| IO     | Input-Output                                    |
| IOT    | Internet of Things                              |
| IP     | Internet Protocol                               |
| LiDAR  | Light Detection and Ranging                     |
| LCMA   | Low-Cost Motor Actuator                         |
| LiPo   | Lithium Polymer                                 |
| MnDOT  | Minnesota Department of Transportation          |
| PAP    | Pocket AVR Programmer                           |
| PC     | Personal Computer                               |
| PI     | Proportional-Integral                           |
| RC     | Remote Control or Radio Control                 |
| RF     | Radio Frequency                                 |
| RGB    | Red, Green, Blue                                |
| RTSP   | Real-Time Streaming Protocol                    |
| SS     | Steady State                                    |
| UART   | Universal Asynchronous Receiver/Transmitter     |
| VAPDA  | Vermont Association of Planning and Development |
| VTrans | Vermont Agency of Transportation                |
| XCTU   | XBee configuration and test utility             |
| YOLO   | You Only Look Once                              |

# Executive Summary

This project reports on the research, development and test of low-cost robotic vehicles, known as Hydraulic Inspection Vehicle Explorers (HIVEs), for the condition assessment of small culverts. This research builds upon previous research to develop improved low-cost robotic culvert inspection systems, i.e., the HIVE 2.0. The motivation is that culvert failures can be expensive and pose public safety hazards. Improved methods of assessing the condition of culverts facilitate the planning of maintenance and replacement projects. The policy of the Vermont Agency of Transportation (VTrans) is to inspect every culvert once every 5 years, resulting in about 9,600 culverts needing to be inspected annually. Culverts with small diameters, i.e. approximately 1-m (36-in) or less, preclude human inspection. The intended use of HIVEs is for small culvert inspections. This report describes the design, build and test of three HIVE variants: 1. HIVE 2.1 – A new and improved robot based on the Sherman tank platform of the HIVE 2.0; 2. HIVE 3.0 – A robot built on the same chassis as the HIVE 2.1, but with more sophisticated capabilities including teaming and increased autonomy; and 3. The HIVE 4.0 – A lower cost HIVE built on a separately sourced chassis.

The HIVE 3.0 while successfully meeting its design objectives and passed field tests was deemed to be too sophisticated for the present practical needs of culvert inspection. The simpler HIVE 2.1 progressed to the stage where it was decided to hold a HIVE Building Workshop at Vermont Agency of Transportation. The workshop was held in Dill Building on January 21, 2026. Eight teams from the various maintenance districts participated, built and took home functioning HIVE 2.1 robots. The HIVE 4.0 built on a generic tracked vehicle chassis holds promise for a cheaper variant similar to HIVE 2.1 with a more robust supply chain. Progress on the HIVE 4.0 has not advanced to the stage where it is ready for routine deployment in culvert inspections, largely due to the need for developing control software.

## **Abstract**

This project reports on the research, development and test of low-cost robotic vehicles, known as Hydraulic Inspection Vehicle Explorers (HIVEs), for the condition assessment of small culverts. This research builds upon previous research to develop improved low-cost robotic culvert inspection systems, i.e., the HIVE 2.0. The motivation is that culvert failures can be expensive and pose public safety hazards. Improved methods of assessing the condition of culverts facilitate the planning of maintenance and replacement projects. The policy of the Vermont Agency of Transportation (VTrans) is to inspect every culvert once every 5 years, resulting in about 9,600 culverts needing to be inspected annually. Culverts with small diameters, i.e. approximately 1-m (36-in) or less, preclude human inspection. The intended use of HIVEs is for small culvert inspections. This report describes the design, build and test of three HIVE variants: 1. HIVE 2.1 – A new and improved robot based on the Sherman tank platform of the HIVE 2.0; 2. HIVE 3.0 – A robot built on the same chassis as the HIVE 2.1, but with more sophisticated capabilities including teaming and increased autonomy; and 3. The HIVE 4.0 – A lower cost HIVE built on a separately sourced chassis.

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# Chapter 1. Introduction

## 1.1 Overview

The need for low-cost, yet effective, methods of inspecting small culverts motivates this research. The nominal definition of a small culvert is a diameter of 1 m (39 in) or less, which precludes human entry and direct visual inspection. This project builds on previous research on improved low-cost robotic small culvert inspection systems, i.e., the HIVE 2.0 (Figure 1), leading to the HIVE 2.1, HIVE 3.0 and HIVE 4.0 (Burton 2020) (Burton 2021).

The policy of the Vermont Agency of Transportation (VTTrans) is to inspect all culverts at least once, with about 9,600 small culverts needing to be inspected annually, typically at a pace of 50 culverts per day during favorable weather (Griffin 2019) (Griffin 2021) (Redmond 2024, personal communication). There are many additional culverts owned by Vermont cities and towns (Vermont Culverts 2025a). An inventory by the Vermont Association of Planning and Development Agencies (VAPDA) located 112,000 culverts with over 16,000 being closed or in poor, critical, or urgent condition (Vermont Culverts 2025b). Improved methods of monitoring and assessing the conditions of culverts facilitate maintenance and the planning of replacement projects, often with substantial cost reduction (Rossow 2012). Several techniques used in current culvert inspection are explained and compared in detail in (Sheth 2018).

As reported in (Gamble 2025a) culvert failures can be expensive and adversely affect public safety and community resilience. Recent culvert failures in Vermont include Berlin (2020) – shut down heavily trafficked road, repairs took 2 years and cost \$839,000 (Delcore 2020) (Occaso 2021); In 2021 a failed culvert under Route 78 in Swanton resulted in a 50-mile detour on a major trucking and commuting road. The failure also caused flooding to a farmer's apple orchard during the 5 months it took to replace the culvert, resulting in multiple failures of his septic system and the death of 50 trees in his business's orchard (Robinson 2021). In 2022 a failed culvert under I-89 near Richmond required 5 months and \$12 million to replace (Minadeo 2022) (Scagliotti 2022). The historic flooding throughout Vermont in the summer of 2024 precipitated numerous culvert failures, along with fatalities (CBS 2024). In July, a culvert in Charlotte failed, with the repair costs being estimated at \$800,000 (Darr 2024). In the same storm event, a breached culvert in Peacham released a flood of water that swept a man off the road in his vehicle, resulting in his death. Estimates for infrastructure repairs in St. Johnsbury, Lyndon, and Plainfield are 3, 8, and 15 million dollars, respectively (Bielawski 2024). In response to the floods of July and August, the Agency of Transportation released \$29.5 million in town highway aid throughout northern Vermont (Heintz 2024).

Feedback from VTTrans personnel indicated that the prototype HIVE 2.0 worked reasonably well but could be improved. One issue was that the plastic tracked treads were too fragile and needed to be replaced with readily available metal tracks. The HIVE is intended for use in mild weather but occasionally needs to work in sub-zero conditions. The inspection cameras were reasonably good, but the images were a little blurry and could be improved. Repairing a balky relay that switches between forward looking and up looking cameras was difficult because of the wiring configuration and waterproofing. The retrieval line needs to be a little heavier. Sunlight occasionally washed out the handheld video monitor. Placing the handheld monitor in the shade of a culvert entrance usually resolved the problem. The telemetry range of the HIVE 2.0 is a significant improvement over that of the HIVE 1.0 but could be improved for further range and clarity of signal transmission. The design of the HIVE 2.0 uses multiple small parts that need to be assembled by hand. One of the primary goals of this project is to simplify the design of the HIVE 2.0 so that the assembly is less tedious.



**Figure 1 HIVE 2.0 (Burton 2020)**

## **1.2 Objectives**

1. Objective 1 – Design, Build and Test HIVE 2.1 – Build a new and improved Hydraulic Inspection Vehicle Explorer based on the Sherman tank platform of the HIVE 2.0. These improvements include ease of manufacture, assembly and maintenance.
2. Objective 2 – Evaluate Performance of HIVE 2.1 in Culvert Tests – Conducted in collaboration with VTrans Project Champion, with the bulk of the activity in the summer seasons.
3. Objective 3 – Deliver Set of Two HIVE 2.1 Robots – These robots will be delivered for use in inspection of small culverts by VTrans maintenance personnel.
4. Objective 4 – Technology Transfer and Guidelines for Implementation including information on the design, fabrication and use of HIVE 2.1.

## **1.3 Anticipated Results and Benefits**

*Benefits of this project* – Culverts are an important aspect of transportation infrastructure. They manage and channel stormwater flow under roadways and other structures. Unexpected culvert failures can lead to cascading damage and expensive repairs. Small culverts are difficult, if not impossible, to inspect with humans. The new and improved HIVE 2.1 robot and related HIVE variants have the potential to enable

efficient and cost-effective inspections of small culverts and provide information for timely maintenance and repair.

*How this project helps VTrans* – The availability of a fleet of HIVE 2.1s will enable cost efficient and effective small culvert inspections with extended range. Being delivered to VTrans are two HIVE 2.1s and the design information so as to readily assemble multiple copies.

*Benefit quantification* – Number of culverts inspected.

## **1.4 Strategic Alignment**

This project aligns with the five VTrans Strategic Goals, outlined in [VTrans Strategic Goals](#).

*Goal 1: Promote organizational excellence by attracting, developing, and retaining a talented, diverse, and engaged workforce.*

The HIVE 2.1 small culvert robot inspection has the potential to improve the ability to inspect culverts in an efficient manner that reduces the tedium of inspection and improves the capabilities of inspectors. This is an emerging technology that makes infrastructure inspection and maintenance a more attractive employment opportunity.

*Goal 2: Grow Vermont's economy by providing a safe, reliable, and efficient transportation system in a state of good repair.*

Small culverts are an integral component of transportation infrastructure. Failure to perform as required, especially during extreme storm and flooding events leads to roadway collapse and washout. Timely maintenance of small culverts helps to prevent and stop many cascading failures at an early stage, thereby reducing overall maintenance costs, increasing safety and providing a cost-effective tool for keeping highway infrastructure in a state of good repair.

*Goal 3: Make Vermont more affordable and serve the vulnerable by providing accessible, convenient, and affordable travel choices.*

Subsurface infrastructure, such as small culverts, being out of sight and out of mind is an often neglected but very important component of transportation infrastructure. Cost-effective methods of inspecting and maintaining small culverts will reduce the cost of roadways and increase the opportunities for providing equitable transportation options.

*Goal 4: Provide a sustainable and energy efficient and advanced technology transportation system.*

Managing stormwater flows is a critical component to maintaining a sustainable transportation system, both by reducing the disruptions and traffic jams that result from unexpected culvert failures. The HIVE 2.1 is an advanced technology system that improves highway inspection and maintenance operations.

*Goal 5: Modernize and improve government efficiency through innovation, continuous improvement, and quality customer service.*

The HIVE 2.1 represents a continued improvement of the innovative HIVE program for inspecting small culverts.

## 1.5 Implementation Plan

*Products from the research* – A set of two HIVE 2.1 robots will be transferred to VTrans, along with a manual for building, using and maintaining the HIVE 2.1 robots.

*How the research will be used* – The HIVE 2.1 robots will be used in the inspection of small culverts.

*The stakeholders or intended audience that will most likely be impacted by the research results* – VTrans personnel responsible for the maintenance and planning of repairs for small culverts.

*Different scales of implementation* – This can be implemented on relatively small scale where the two HIVE 2.1s will be used by a small group of VTrans culvert inspectors. A larger scale would be to assemble multiple HIVE 2.1s to be used on a state-wide basis. The ubiquity of the need for inspecting small culverts could extend the use nationwide.

*Potential impediments to implementation* – The biggest potential impediment is supply chain disruptions. Most of the parts are readily available from standard vendors, but there is a risk that some parts may be unexpectedly unavailable.

*Activities necessary for successful implementation* – 1. Acquire the necessary parts to reduce the risk of supply chain problems. And 2. Work closely with VTrans Project Champion and other VTrans maintenance personnel to ensure that the HIVE 2.1 design meets expectations.

*Costs* – Costs of various inspection crawlers are presented in Table 1. The \$80,000 crawler system previously used by VTrans (Figure 9) is considered standard market price. The options between \$20,000 and \$35,000 are considered to be inexpensive options. Of these commercial options, the Fiberscope Troglogator is the only wireless option (it is difficult to find wireless crawlers available commercially). The sub-thousand price point of the HIVE 3 drastically redefines the definition of inexpensive inspection crawlers.

**Table 1 HIVE costs compared to commercial crawlers (price ca. 2025 without tariffs).**

| Crawler                | Cost           | Reference             |
|------------------------|----------------|-----------------------|
| HIVE 4.0               | \$300          | N/A                   |
| HIVE 2.1               | \$450          | N/A                   |
| HIVE 3.0               | \$425 to \$810 | (Gamble 2025a)        |
| HIVE 1.0               | \$1,300        | (Youngblood 2017)     |
| HIVE 2.0               | \$1,500        | (Burton 2020)         |
| Foxtech Gopher-20      | \$22,000       | (Foxtech 2025)        |
| Dakotah Pipe Crawler   | \$28,995       | (MDPE 2025)           |
| Insight Iris           | \$34,645       | (Insight Vision 2025) |
| Fiberscope Troglogator | \$34,800       | (FiberScope 2025)     |

## Chapter 2. Design and Performance of HIVE 1.0 and 2.0

The concept of the Hydraulic Inspection Vehicle Explorer originated with the HIVE 1.0 (previously denoted HIVE) developed by MnDOT (Coughlin 2016) (Langlie 2016) (Griffin 2019) (Youngblood 2017). In addition to being lightweight and low-cost, a primary advantage of the HIVE 1.0 is that it is lightweight, low-cost, and can be operated by a single inspector without a specialized support vehicle. While being somewhat of a breakthrough disruptive technology, the HIVE 1.0 has a limited video telemetry range of about 40 feet (12.2 m) through an 18-inch (0.46 m) diameter culvert, and the four-wheel drive configuration gets stuck in gaps and has difficulty maneuvering past obstacles in culverts (Masada 2017).

The development of the HIVE 2.0 built on the success of the HIVE 1.0 while improving upon some of the shortcomings. The result was a system based on a hobby Sherman tank chassis with tracked treads and improved video telemetry with a First Person View (FPV) camera system that operates on a 5 GHz band, Figure 3. The tank tread configuration enables traversing of more rugged conditions inside the culvert. The 5 GHz band proved to be much better than lower frequency 2.4 GHz and 900 MHz inside small diameter culverts. It is believed that the improvement is due to the lossy waveguide nature of electromagnetic wave transmission in culverts favoring the 5 GHz band through line-of-sight transmission (Burton 2020) (Burton 2021). Table 2 lists the requirements, specifications and performance of the HIVE 1.0 and HIVE 2.0.



**Figure 2 HIVE 1.0 used by VTrans with articulated Sony Action Cam video camera mounted on two servo motors (Burton 2020)**

**Table 2 HIVE 1.0 and 2.0 Requirements, Specifications and Performance**

| <b>No.</b> | <b>VTrans Requirements</b>                             | <b>Engineering Specifications</b>                                                           | <b>HIVE 1.0</b>             | <b>HIVE 2.0</b>     |
|------------|--------------------------------------------------------|---------------------------------------------------------------------------------------------|-----------------------------|---------------------|
| 1          | Capable of fitting inside small culverts               | Maximum vehicle height of 8 inch (203 mm)                                                   | Meets specification         | Meets specification |
| 1          | Capable of fitting inside small culverts               | Maximum vehicle width of 9 inch (229 mm)                                                    | Meets specification         | Meets specification |
| 2          | User capable of easily viewing live footage            | Live footage shall be viewable on iPad or tablet                                            | Meets specification         | Meets specification |
| 3          | Footage available deep into small culverts             | Live footage shall be viewable at least 80' (24.4 m) into 18 inch (0.457 m) culvert         | Does not meet specification | Meets specification |
| 4          | Footage available through drop inlets                  | Live footage shall be viewable at least 80' (24.4 m) into culvert with drop inlet           | Does not meet specification | Meets specification |
| 5          | User capable of viewing all sides of pipe, with camera | Camera shall view all sides of 3' (0.914 m) culvert within 2' (0.610 m) of front of vehicle | Meets specification         | Meets specification |
| 6          | Capable of traversing through culverts                 | Vehicle shall travel through sediment sludge                                                | Meets specification         | Meets specification |
| 6          | Capable of traversing through culverts                 | Vehicle shall travel over a step change in height of at least 2 inch (5.080 cm)             | Meets specification         | Meets specification |
| 6          | Capable of traversing through culverts                 | Vehicle shall travel up slope of at least 20-degrees                                        | Meets specification         | Meets specification |
| 7          | Capable of crossing separation gap in pipes            | Vehicle shall span a gap of at least 6 inch (16.240 cm)                                     | Does not meet specification | Meets specification |
| 8          | Capable of functioning in water                        | Vehicle shall drive through 4 inch (102 mm) of water                                        | Meets specification         | Meets specification |
| 9          | Capable of stopping from rolling down hills            | Vehicle shall remain still on 20-degree slope                                               | Does not meet specification | Meets specification |

|    |                                                           |                                                                                                       |                                |                     |
|----|-----------------------------------------------------------|-------------------------------------------------------------------------------------------------------|--------------------------------|---------------------|
| 10 | Equipped with cable for retrieving vehicle                | 1/16 inch (0.159 cm) stainless steel cable shall attach to rear of vehicle                            | Meets specification            | Meets specification |
| 11 | User capable of knowing vehicle's location                | User shall know vehicle's distance in culvert to+/- 1' (305 mm) in culvert at all times               | Moderately meets specification | Meets specification |
| 12 | User capable of releasing cable at end of tunnel          | Cable shall be detached in less than 30 seconds                                                       | Meets specification            | Meets specification |
| 13 | One user capable using and carrying all system components | Vehicle shall be setup and used by one person                                                         | Meets specification            | Meets specification |
| 13 | One user capable using and carrying all system components | All system components shall weigh no more than 30 lbs (0.454 kg) collectively                         | Meets specification            | Meets specification |
| 13 | One user capable using and carrying all system components | All system components shall fit in a 24 inch x 15 inch x 15 inch (0.610 x 0.381 x 0.381 m3) container | Meets specification            | Meets specification |
| 14 | Affordable                                                | One system shall cost no more than \$2,500                                                            | Meets specification            | Meets specification |



**Figure 3 Foxeer Falkor FPV camera used in HIVE 2.0 (Burton 2020)**

The HIVE 2.0 uses two Foxeer Falkor FPV cameras to transmit video data inside the culvert. One looks forward. The other looks up. The cameras have a high-quality image of 1200 television lines (TVL) and a wide 155-degree field of view. The use of two cameras and a single video transmission channel required switching of channels and an upgraded RadioLink AT10 radio controller (RC) with R12DS receiver/relay

controller. Testing with the Foxeer camera and RadioLink AT10 controller on the HIVE 2.0 found that the range of the video telemetry link had a was shorter than the range of the RC.

## **Chapter 3. Design and Performance of the HIVE 2.1**

The HIVE 2.1 is a simplified variant of the HIVE 2.0 that is easier to build, yet performs as well, if not better. The design requirements for the HIVE 2.1 are similar to that of the original HIVE 2.0, as specified in Table 2. The HIVE 2.1 uses a lower cost, high performance video telemetry system based on the AMB82. The HIVE 2.1 had some key modifications to its required attributes. Firstly, a new requirement is that the tank be easily constructed at a low cost. The goal of less than 1 hour of build time. This requirement came from the HIVE 2.0, which require substantial time and effort to construct. The second requirement modification was the level of maintainability. The 2.0 had a relatively sophisticated electrical system requiring many connecting wires to function. These wires proved to be a maintenance challenge for identifying and troubleshooting issues that could arise. The design of the HIVE 2.1 aims to vastly reduce the number of wires required in the fully functional tank along with the number of electrical components in the final design.

### **3.1 General Design Choices**

The HIVE 2.1 uses the Heng-Long M4A3 Sherman tank with the TK-7.0 as the main board. Maneuverability of the tank was well established by the HIVE2.0, meeting the mobility and size requirements. The built-in electronics consist of a main control board that is fed power from a 7.2V NiMH battery. This board is an all-in-one design that contains the radio receiver, motor control, and power distribution systems. The board has many unused control pins that allow for their use in powering the tank camera system. The decision to use this board was based on it being well-engineered and being effective at heat management, and replacing it requires extensive modification of the tank, which violates the simplicity requirements. Working with the existing control board locks in the choice of RC transmitter and receiver(built into the TK-7.0) to that which comes with the tank. This proved to be an acceptable outcome for a single tank system when open-air range testing showed the tank still functioning at over 500 feet from the transmitter (Burton 2021).

### **3.2 Structural Changes**

A key simplification with the HIVE 2.1 was to remove the turret. The HIVE 2.0 kept the existing turret along with turret rotation capability. Turret rotation was deemed an unnecessary feature that required extensive physical modifications to allow cameras and transmitters to be mounted inside. Removing the turret entirely from the final design opened up a hole at the top of the tank for use later on in the build.

### **3.3 Camera System**

The main camera inspection system requirements are to be simple, cheap, and consist of as few parts as possible. The Realtek AMB 82-mini development boards meets these requirements with Wi-Fi access points that transmit wide-angle video live at either 2.4 GHz or 5 GHz frequency using RTSP (Real-time streaming protocol) at an adjustable bit rate. Two AMB-82 boards were positioned in the opening on the top of the tank opened by the turret removal. One of these boards directed its camera upward, while the other pointed in forward. The combination of the two views creates a satisfactory field of view for inspecting the inside of the culvert pipes.

The two AMB 82-minis connect to a receiver via a Wi-Fi access point (AP). Both devices were act as cameras; however, only one acts as an access point. The other connects to it and feeds video. This allows a laptop to be connected to the access point AMB 82 and for it to act as an Internet Protocol (IP) camera to the laptop. Any device capable of viewing RTSP IP camera streams can access both RTSP streams from their IP addresses (Schulzrinne 2025). Figure 4 shows the overall system configuration, magnetic counter circuit, and video feeds from two cameras inside of a culvert.

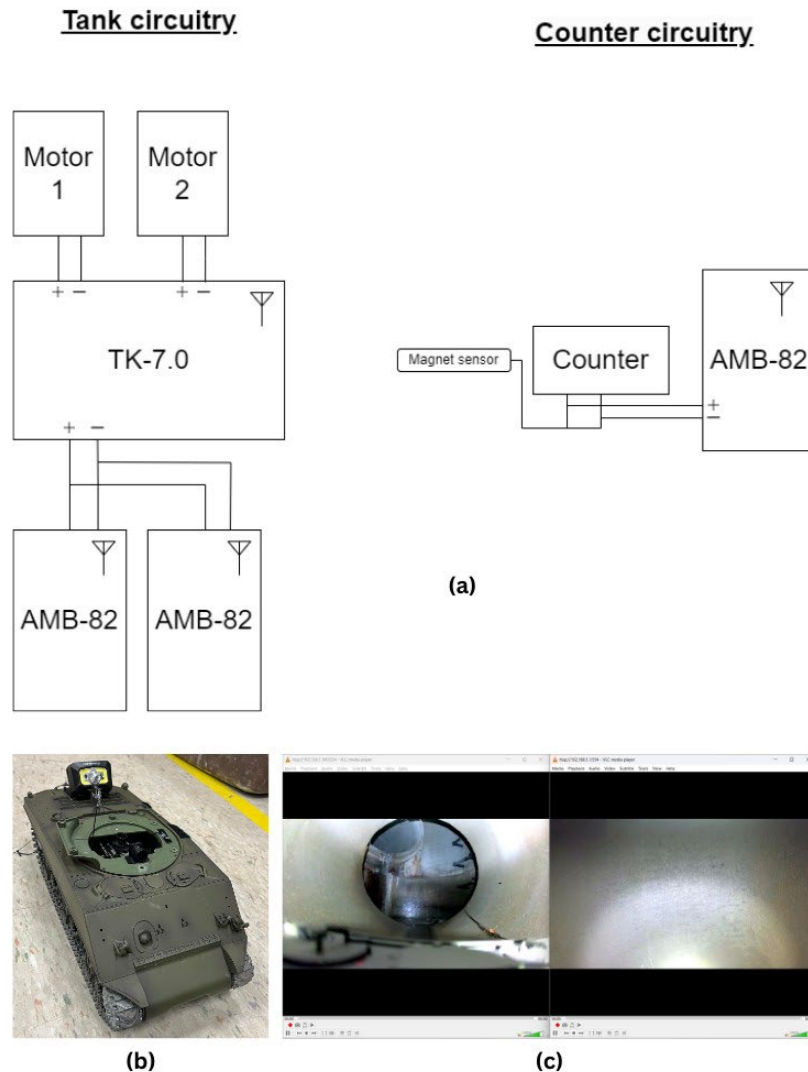


**Figure 4 (a) Tank and Counter Circuits (b) Tank-chassis inspection robot (HIVE 2.1) (c) Remote view seen by the inspector simultaneously from top and front cameras**

### 3.4 Transmission Improvements

RTSP - Preliminary testing with the AMB-82 showed some signal transmission problems. This led to multiple changes being made to maximize transmission quality. HIVE 2.1 originally used an HTTP transmission. Changing to RTSP increased signal reliability and range. Despite the higher packet loss for RTSP as shown in the research work by (Firmansyah 2022), we saw a better inspection video feed with RTSP. Moreover, with developing a multi-tank system to inspect complicated culvert systems as a

potential future goal would make it a MANET network in which RTSP outperforms HTTP in other crucial parameters like throughput and delay. The operations program, also has a delay that decreases the chances of video buffering.

RTOS - A Real-Time Operating System (RTOS) using the FreeRTOS framework enhances the performance and quality of the video streaming system. The implementation is on the AMB-82 mini board, which has two cores. RTOS allowed use of both cores by doing two tasks simultaneously: streaming video over RTSP and establishing and maintaining a Wi-Fi connection. The setup established two FreeRTOS tasks with 4096-byte stack sizes and a priority of one each, with the Wi-Fi task managing Wi-Fi connectivity and the video streaming task handling video data transfer. The Wi-Fi task repeatedly tries to establish a connection, indicating its status and retrying if required. The video streaming task guarantees that the stream is broadcast as long as the Wi-Fi connection is operational. This concurrent execution optimizes system resources and improves the overall video quality. The code with RTOS implementation proved to be better than the code with non-RTOS implementation. Since the AMB-82 is also widely used for AI on edge device applications, using its resources efficiently makes it ideal for any future lightweight real-time defect detection systems.

Antenna - The AMB-82 boards came with a small patch antenna (RT-PCB162 V0.0.) The antenna on the AMB-82 that acts as the access point antenna, is replaced with a higher gain antenna, the ANT-W63-FPC-SH100M4. This antenna has a gain of around 7.8 dBi in the 5150-5800Ghz frequency range used with the final tank configuration as opposed to the max gain of the built-in antenna in the same frequency range of around 0.84 dBi. The actual transmission frequency of the AMB 82 in the 5G band was found to be around 5.18 GHz using a FieldFox analyzer, Table 3.

**Table 3 Antenna Gain Readings with FieldFox Analyzer**

| Antenna             | Frequency | Reading    |
|---------------------|-----------|------------|
| RT-PCB162 V0.0      | 2.4 GHz   | -6.5 Dbm   |
| RT-PCB162 V0.0      | 5.18 GHz  | -20.1 Dbm  |
| ANT-W63-FPC-SH100M4 | 2.4 GHz   | 0.5 Dbm    |
| ANT-W63-FPC-SH100M4 | 5.18 GHz  | -14.07 Dbm |

USB Wi-Fi adaptor - Using an external high-gain USB adaptor for the laptop increases the range and repeatability of the telemetry. The adaptor of choice was the (Archer T2U Plus AC600 High Gain Wireless Dual Band USB Adapter). The selection was based on signal range testing reported by the NYT (Domingo 2024) and because of its low price point and simple design.

Frequency - AMB-82 boards have the ability to create Wi-Fi access points in either the 2.4 GHz or the 5GHz frequency range. From testing with a Field Fox spectrum analyzer, the 5GHz band produced a signal closer to the 5.18GHz range. This, along with the choice of antenna was tested. The ANT-W63-FPC-SH series patch antenna was used to enhance the signal. As per its technical specifications, it has a max gain of 4.7dBi in the 2400-2500Mhz band and a max gain of 7.8 dBi in the 5150 MHz to 5895MHz band.

Waveguide - A previous study by (Burton 2021) used 5.8 GHz and 1.2 GHz bands, which were seen to perform better than 2.4 GHz. The 5.8 GHz reached a distance over three times further than 2.4 GHz in their testing. The rationale was that the culvert acted as a lossy waveguide which adversely affects the longer wavelength 2.4 GHz band, while the shorter wavelength 5.8 GHz operates in more of line-of-sight

mode that avoids the lossy walls of the culvert (Engan 2006). Our system could operate in either the 2.4 or 5.18 GHz ranges, so the 5.18 GHz band was anticipated to perform better, but both were tested.

**Reel system** - A two-spool system proves to be a more accurate vehicle location tracking system than the single-spool system used in HIVE 2.0. Steel cable or high-strength braided fishing line can be used.

The two-spool system retrieves the HIVE 2.1 and measures its depth into a culvert with a large cord reel. This reel had a uniform diameter central rotating core, allowing consistent measurements. Unfortunately, as testing proceeded, it became clear that the line would pile up, as shown in the Figure 5.a, and thus change the diameter of the spool and cause errors in readings of any significant distance. Adding a second reel resolved many of these problems. This reel allowed for a more accurate distance measurement because the line was all spooled on the first reel (Black reel in figure 3b,3c), and the second only took two wraps of the line; as the vehicle unspooled the reels, the second reel would have its turns counted instead (Red reel, Figure 3b,3c). Because of its lack of built-up line, it would have to sustain a uniform diameter throughout the test. At a measurement 156 feet in length the single spool was off by just over 15 feet while the double spool was off by around 1.5 feet. The error is believed to be due to slight variation in the diameter of the red spool.

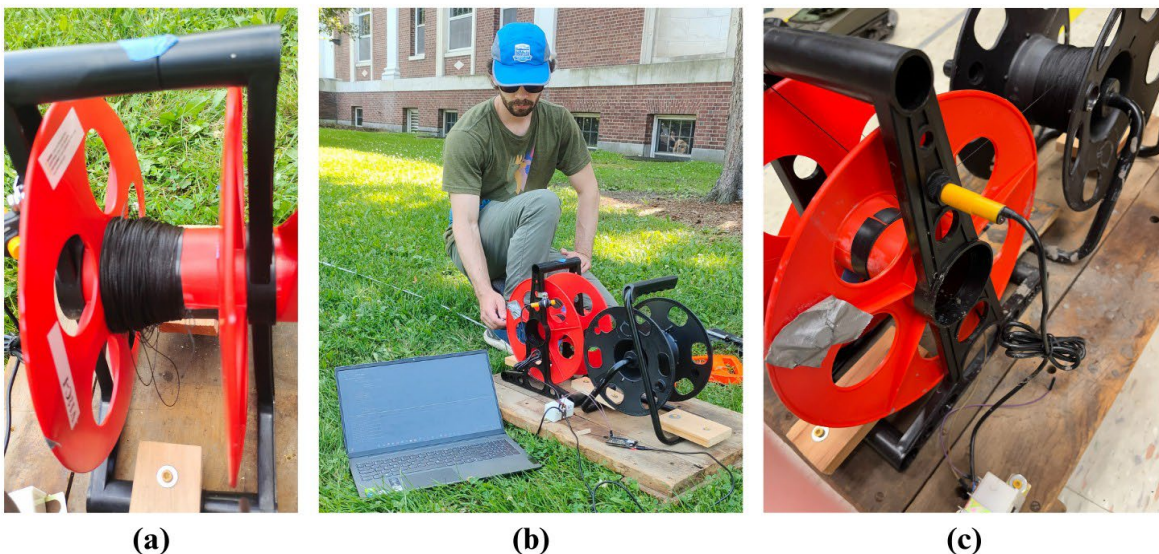


**Figure 5 (a) Piling problem with the single spool system (b) Two-spool system for accurate location tracking (c) Mounting of the electronic counter to the two spool-system**

**Location tracking framework** - The basic approach is to count the number of rotations or turns of the spool, then determine the distance traversed by the tank by multiplying it by the circumference  $\text{Distance} = \text{Rotations} * \text{Circumference}$ . The mounting of an electronic counter with a magnet was simpler than 3D-printing a custom mount with a rotary encoder. Probed into this electronic counting system with an AMB82 determines the pins that give a voltage spike when the magnet attached to the rotating spool comes in proximity. The time is taken care of by the millis function. Once the inspection starts, the output is an array in which the first element is the distance traversed, and the second element is the timestamp. This output can be stored on the micro-SD card in AMB82 for use in later analysis.

### 3.5 Field Tests: Performance of Hive 2.1

*36-inch Concrete Culvert* – Multiple tests were conducted inside a culvert located at (-73.187872 44.472881) Degrees. This culvert is not officially marked on VTculverts.org. The culvert was measured around 200 feet and provided a good testing site for the configuration and integration of the HIVE2.1 system. In fact, as noted in (Burton 2021), concrete culverts do not behave as conventional radio frequency waveguides because of their highly absorptive walls making the signal attenuate. Thus, in this re- search, most of the testing is done in this culvert, finding the optimal parameters in the worst-case scenario. Extensive testing at this location determined a favorable configuration that consistently reached the full length of the culvert with no video disruption of either camera feed.

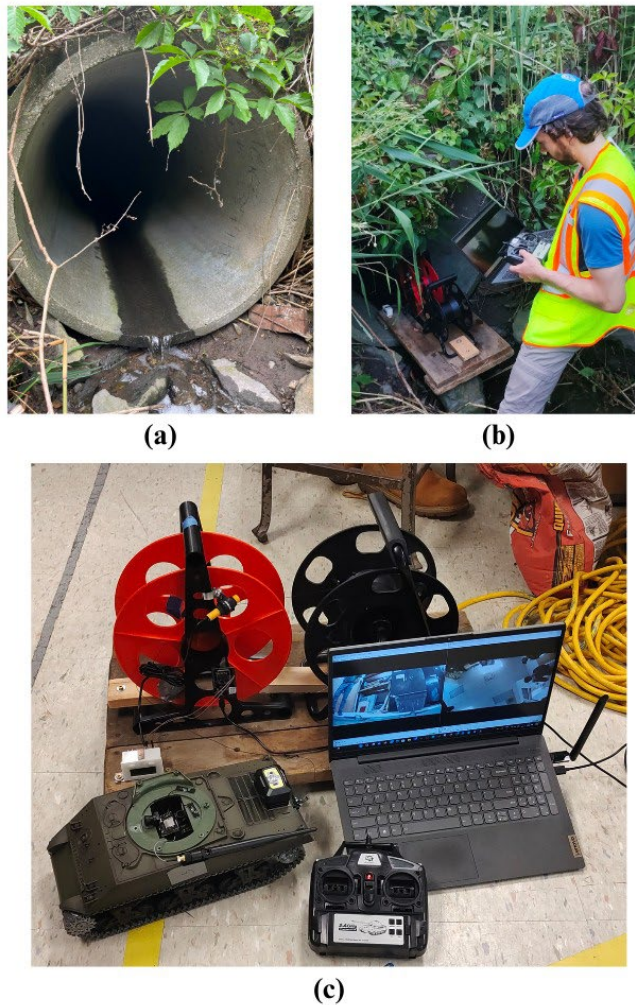


**Figure 6 (a) Concrete culvert - 36 inches (b) Demonstration of the inspection (c) Components comprising the entire inspection system**

The initial tests used the smaller patch antenna that comes along with the AMB-82 to check signal quality. Later tests used a higher gain antenna. Different parameters like the video bit rate, latency (video caching) and network band were checked to get the optimal configuration parameters.

The field tests were evaluated qualitatively, considering the point of view of an inspector – primarily checking for the video quality and buffering in the video feed. In a test with the smaller patch antenna, an inspection test run was done with an RTOS-optimized code and a non-RTOS version with the rest of all the parameters kept the same. The video quality was slightly better with the RTOS version and there was serious video buffering (stuttered 3 times) in the non-RTOS inspection run. For confirmation, the same test was run twice and the results were consistent. Hence, all the further tests were performed with the RTOS-optimized code. A similar scenario is the USB Wi-Fi adapter and the internal laptop antenna. Results reported below used the external USB Wi-Fi adapter. A concise listing of the evaluated different parameters tried out, and their visual evaluation appears in Table 4. Qualitative video quality is evaluated using two parameters - Video Buffering and Visual Quality, which are defined as:

Video Buffering - The number of significant video stutters observed during the inspection run

Visual Quality (VQ) - Qualitative estimation of the video quality (rated out of 10), where '10' is the video quality of the feed from HIVE 2.0

**Table 4 Field Testing of HIVE 2.1**

| Antenna             | Frequency | Bitrate | Latency | Video Buffering | VQ  |
|---------------------|-----------|---------|---------|-----------------|-----|
| RT-PCB162 V0.0      | 2.4 GHz   | 1 Mbps  | 200ms   | 4               | 7   |
| RT-PCB162 V0.0      | 2.4 GHz   | 1 Mbps  | 100ms   | 3               | 7   |
| RT-PCB162 V0.0      | 2.4 GHz   | 1 Mbps  | 50ms    | 3               | 7   |
| RT-PCB162 V0.0      | 2.4 GHz   | 2 Mbps  | 100ms   | 5               | 8   |
| RT-PCB162 V0.0      | 2.4 GHz   | 4 Mbps  | 100ms   | 4               | 5   |
| RT-PCB162 V0.0      | 2.4 GHz   | 12 Mbps | 100ms   | 3               | 5   |
| RT-PCB162 V0.0      | 5 GHz     | 1 Mbps  | 100ms   | 1               | 7   |
| ANT-W63-FPC-SH100M4 | 2.4 GHz   | 1 Mbps  | 100ms   | 2               | 8   |
| ANT-W63-FPC-SH100M4 | 5 GHz     | 1 Mbps  | 100ms   | 0               | 8.5 |
| ANT-W63-FPC-SH100M4 | 5 GHz     | 2 Mbps  | 100ms   | 0               | 9   |

18-inch PVC Culvert – Testing at an 18-inch corrugated plastic culvert location latitude 44.428322 longitude -73.211754 with ID: 31b8b219-595f-4dd9-9dd9-1928f73d57d5 located just off route 7 in South Burlington, VT (Vermont Culverts 2025a). The goal of this testing was to ensure that the tank reached the 80-foot transmission depth requirement. The testing proved that it was; however, the remote control range of the tank only reached a depth of 82.2 feet before losing control in this environment. The tank's video transmission reached 109.68 feet before running out of space to continue, never losing connection. Similar results were obtained using a newly built HIVE 2.1 in 18-in PVC lined culverts in Ferrisburgh, VT where the video feed at 5 GHz continued strong at 90 ft (approx.) while the RC signal at 2.4 GHz lost connection and tank control, Figure 8. Of note is this test used a small handheld tablet, instead of a laptop PC, to view and record the video feed and the stock antennas on the AMB-82.



**Figure 7 18-inch corrugated plastic culvert inspection setup**



**Figure 8 Testing of HIVE 2.1 in drop inlet in Ferrisburgh, VT, August 30, 2025. Second operator on left holds a small handheld tablet that reads and records the video feed.**

### **3.6 HIVE 2.1 Observations and Discussion**

**Optimal video bitrate** - It was observed that the best visual quality appeared with a video bitrate of 2 Mbps. In fact, for RTSP streaming on AMB82-mini, it is officially recommended to lower the bitrate to 2 Mbps to account for possible network congestion, (AMB 2025) which was confirmed by the tests. With higher bitrates, the video feed becomes very streaky, has worse performance than the 1 Mbps test, and is less fit for inspection.

**Fixing upon a latency value** - From the inspection test runs and general observation, 100ms latency was best for good inspection and decent video feed quality. Hence, for the tests with the better antenna (ANT-W63-FPC-SH100M4), latency was no longer varied.

**Unexpected performance of the RT-PCB162 V0.0 antenna in 5 GHz** - As mentioned in the 'Antenna' section, the gain of this antenna is very low (0.84 dBi) in the 5 GHz as per the datasheet, so poor performance was expected. The performance was slightly better than its 2.4 GHz counterpart. Further testing confirmed that the antenna transmitted at 5 GHz. It was concluded that the better performance was due to the lossy waveguide effect. Therefore, to make better use of this, we chose to use a better antenna that has a higher gain in the 5 GHz band.

The use of the higher gain antenna (ANT-W63-FPC-SH100M4) showed improvement in the test results, and the number of times there was significant video buffering has drastically reduced with a slight improvement in quality as well. Despite the occurrence of grainy video feeds in rare instances, the best parameters of inspection were concluded to be (5 GHz, 2 Mbps, 100ms).

## Chapter 4. Design and Performance of the HIVE 3.0

The HIVE 3.0 extends HIVE technology with for culvert inspection with low-cost, easy-to-build, semi-autonomous swarm robots. The following is an abbreviated version of the results reported in more detail in the M.S. thesis by Brandon Gamble (Gamble 2025a) (Gamble 2025b).

Culverts, being radio absorptive and GPS denied, present significant telemetry and navigation challenges. The swarm of autonomous follower robots enable inspection of long and complex culverts, by using each robot as a relay node in a network to transmit video and control signals between the user and the lead robot.

Two leader tracking methods are studied. The first utilizes RGB-D video for intelligent leader and obstacle detection and following. The second utilizes only RGB or grayscale video for leader detection and following, at the cost of obstacle detection but benefiting from significantly less expensive hardware: about 1% the cost of typical culvert inspection robots. Another primary development is an inexpensive universal dual motor control board. The entire HIVE 3.0 system uses a scalable and modular platform with capabilities in a variety of applications, such as search and rescue, structural health monitoring, and radar surveying using additional sensors.

### 4.1 Motivation

Commercially available culvert inspection vehicles are quite useful, but have a number of down sides, including cost, weight, and bulky tether cables. (Gamble 2025a) (Gamble 2025b). Some crawlers even require a van or trailer as a mobile control station, and multiple support personnel. Inspection crawlers cost anywhere from \$20,000 (Foxtech 2025) to \$80,000 (Burton 2020). The crawlers alone typically weigh 35 pounds and with a required tether system weigh upwards of 325 pounds. Nearly all crawlers include a tether system: a steel cable for retrieval and a data cable for transmitting control and video signals. These cables can either be separate or integrated together into one thick cable. These cables are heavy and introduce large amounts of friction when inspecting long culverts, especially those with corners. The goal of the HIVE family is to develop a vehicle for state and municipal transportation agencies to inspect culverts that is easy to assemble, repair, and operate while also being inexpensive and built from widely available components.



**Figure 9 Commercial inspection vehicle used by VTrans (Burton 2020).**

The HIVE 2.0 (Figure 1) was developed by the University of Vermont (UVM) in 2020. Primary design goals were to improve telemetry and terrain traversal without increasing cost significantly. Migrating to a tank chassis increases maneuverability. Control signals transmitted at 2.4GHz demonstrated 34m range and video signals transmitted at 5.8GHz demonstrated 44m range in a small culvert where telemetry is especially challenging. These results were achieved, while only increasing the price of the unit to \$1,500. However, the HIVE 2.0 is limited to line-of-sight inspection by wireless telemetry (Burton 2020).

## 4.2 HIVE 3.0 System Overview

As previously noted, culverts provide telemetry challenges. RF range within culverts is significantly less than in open air. Signals do not transmit around corners due to the absorptive and lossy quality of culvert surfaces. The operating principle of the HIVE 3.0 (Figure 10) utilizes a swarm of vehicles to deploy a network of RF devices. The RF device configuration is to act as a relay system to transmit control and video signals between the lead vehicle and the user. Intermediate vehicles autonomously follow one another. A key benefit is the ability to relay signals around culvert corners, allowing deeper inspections into more complex culverts that were previously not inspectable.



**Figure 10 HIVE 3.0, smart-follower configuration.**

The HIVE 3.0 system is designed to be both modular and scalable: the control electronics are easily adapted to any differential drive robot (DDR) following the methods described herein. While the design intent of the HIVE is culvert inspection, it can be used in many other applications such as search and rescue, structural health monitoring, and radar surveying. These applications can be achieved with additional sensors such as LiDAR, radar, temperature and humidity, or inclinometer (Fath 2024).

Furthermore, the design intent of the HIVE 3.0 aims to reduce unit cost below \$1,000. The use of inexpensive and widely available components not only keeps unit cost down but also helps to make repairs easy and inexpensive.

**Cost Summary** – The costs of the various HIVE 3.0 configurations are summarized in Table 5 in early 2025 prices. The leader is the most inexpensive configuration at just \$426. Even the most expensive configuration, the smart-follower, is only \$808: nearly half the cost of the HIVE 2.0.

**Table 5 Total costs of various HIVE 3.0 configurations (ca. 2025 with no tariffs)**

| Configuration  | Base Cost [\$]   | Additional Cost [\$] | Total Cost[\$] |
|----------------|------------------|----------------------|----------------|
| Leader         | 367.80 (Table 9) | 57.99 (Table 12)     | 426            |
| Basic-Follower | 367.80 (Table 9) | 106.12 (Table 14)    | 474            |
| Smart-Follower | 367.80 (Table 9) | 440.12 (Table 15)    | 808            |

*Software and Libraries* – Software languages for this project include Python 3.10 for the Raspberry Pi and the Arduino variant of C++ for the LCMA. Notable Python libraries include OpenCV and pyrealsense2. OpenCV is an open-source real-time computer vision library that contains functions used for tracking ArUco markers. pyrealsense2 is a Python wrapper for the Intel RealSense SDK which is written in C++. BJG\_TB6612FNG is a custom C++ library written for convenient control of dual-channel H-bridges. It is used within the LCMA scripts.

### 4.3 Depth Estimation

Two methods for depth estimation are used by the HIVE, depending on its configuration: 1. Stereoscopic depth estimation and 2. Known object size. Stereoscopic depth estimation uses two images of the environment taken from slightly different perspectives and estimates depth by measuring the parallax between the images. Known object size uses trigonometry to map the pixel dimension of an object as it appears in an image to its distance from the camera based on the known physical size of the object and the specifications of the camera view.

*Stereoscopic Depth Estimation* – The RealSense D435i camera does not directly measure depth. Instead, it produces depth images using stereoscopic depth estimation. The foundation of stereoscopic depth estimation is the link between disparity and depth (Gamble 2025a).

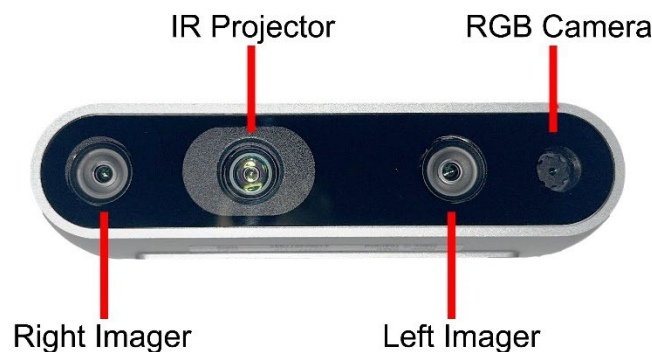


**Figure 11 Cameras and projector on RealSense D435i.**

Disparity is a feature of the parallax effect, wherein the position of an object varies in the scene when comparing two different viewpoints. The RealSense D435i uses two parallel cameras (“imagers”) offset by 50 mm to produce stereoscopic image pairs, Figure 12.

In a stereoscopic image pair, pixels corresponding to the same object will have different locations in each image as described by the parallax effect. Disparity is the distance between these varying pixel coordinates, as illustrated in Figure 12. With disparity measured, depth is approximated as follows (Luxonis 2025) (Mansour 1990):

$$d_{mm} = y_{px} \cdot \frac{B}{\delta}$$

**Equation 1. Depth approximated from disparity**

here:

$d_{mm}$  = distance of the object [mm]

$y_{px}$  = apparent focal length of the camera [px]

$B$  = baseline distance between viewpoints [mm]

$\delta$  = disparity [px]

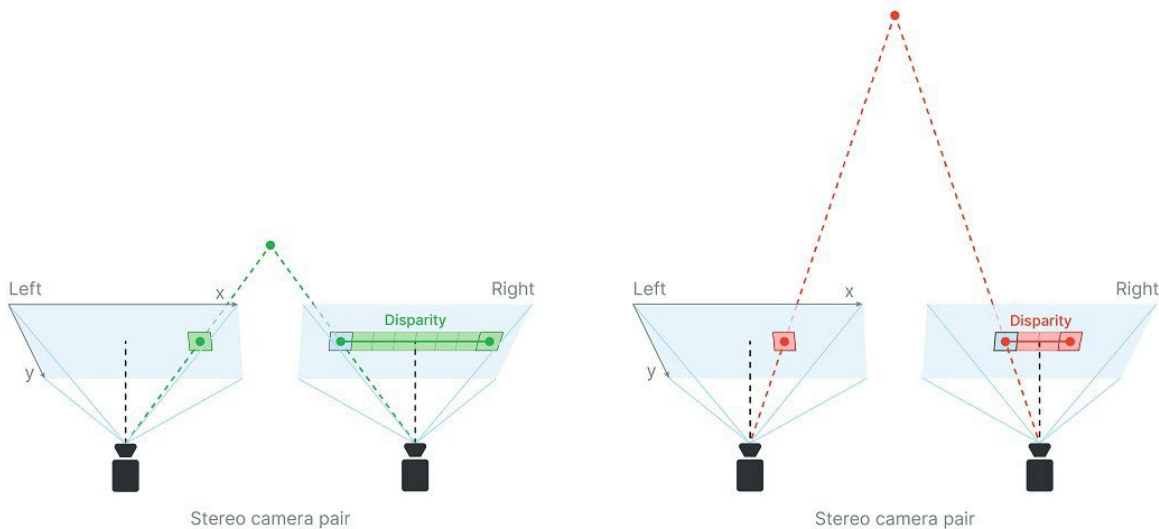


**Figure 12 Example of disparity in near and far objects (Luxonis 2025).**

*Known Object Size* – Stereoscopic depth estimation with dot matrix projection provides a full depth map of the environment but requires expensive camera devices. The D435i, as previously noted, costs \$334. It is not always necessary to have access to a full-depth image of the environment. For example, if the goal is to follow a leader in an obstacle-free path, it is only necessary to know the location of the leader. In this

case, an inexpensive RGB camera and fiducial marker of known size can be used to determine distance and heading of the leader for tracking. Raspberry Pi camera modules cost as little as \$12.95, which would cut the cost of the HIVE 3.0 by \$321.05, reducing the total cost by 47%.

In order to find the distance and heading using a flat image, similar triangles of the projected image and the real environment (Figure 13) are analyzed:

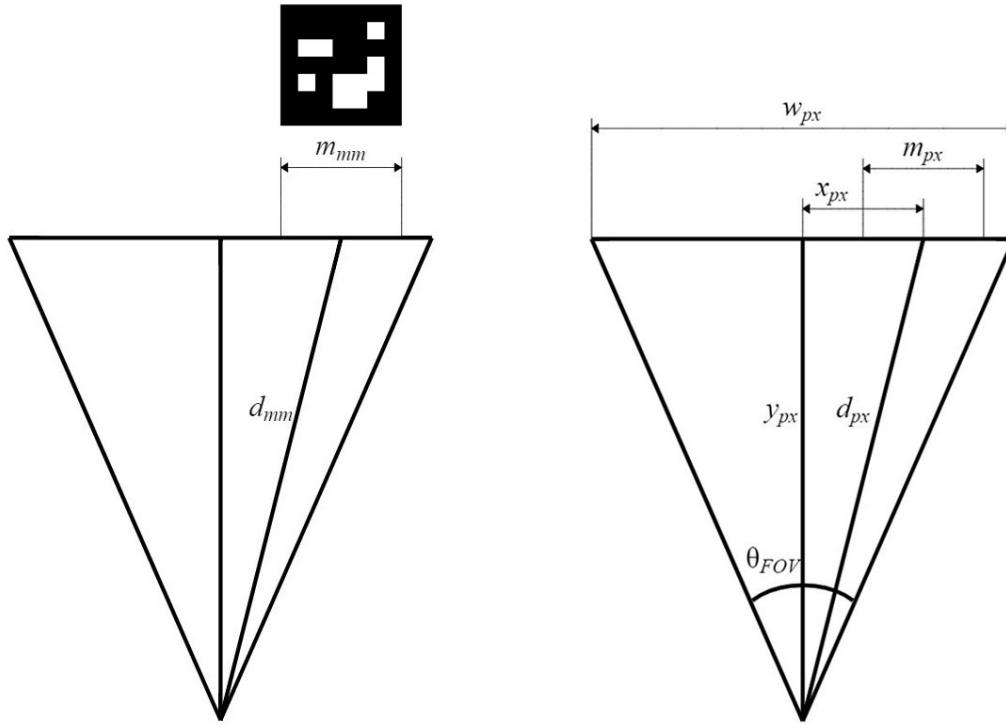


**Figure 13 Similar triangles of known object size. Left: physical-space. Right: image-space. (Gamble 2025a)**

$$\begin{aligned}
 d_{mm} &= \frac{m_{mm}}{m_{px}} d_{px} \\
 &= \frac{m_{mm}}{m_{px}} \sqrt{x_{px}^2 + y_{px}^2}
 \end{aligned}$$

#### Equation 2 Distance estimate

here:

$m_{mm}$  = physical size of marker [mm]

$m_{px}$  = projected size of marker [px]

$d_{px}$  = apparent distance of marker from camera [px]

$x_{px}$  = distance between center of marker and center of image [px]

$y_{px}$  = apparent distance of image from camera [px]

In practice,  $y_{px}$  and  $m_{mm}$  are constants, with  $y_{px}$  being computed once at run-time. Variables measured during tracking are  $m_{px}$  and  $x_{px}$ . These four values are plugged into Equation (2) to approximate marker distance.

#### 4.4 ArUco Markers

(Gamble 2025a) describes in detail ArUco marker generation, detection and depth estimation. Figure 14 shows three sequential markers from the N5x5 M50 library. Libraries are defined by N, the bit size (not including the 1-bit black padding), and M, the number of markers in the library. Each marker in a library has a unique ID number from 0 to M-1. Additionally, marker sizes can be associated with specific marker ID numbers. In this way, markers of various sizes can be used simultaneously to identify objects, such as other HIVEs, and determine the relative distance. Figure 15 shows a camera image with ArUco markers. Figure 16 shows ArUco markers detected with thresholding of edges.

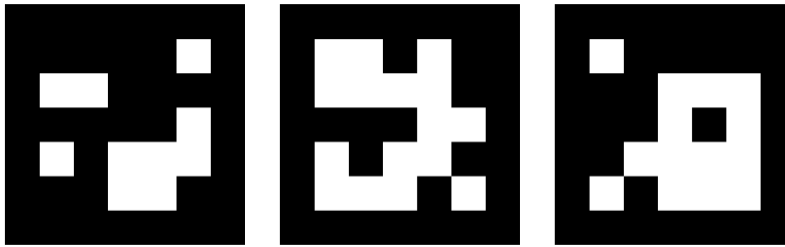


Figure 14 ArUco markers of N5x5 M50 library. Left to right IDs 1, 2, 3. (Gamble 2025a)

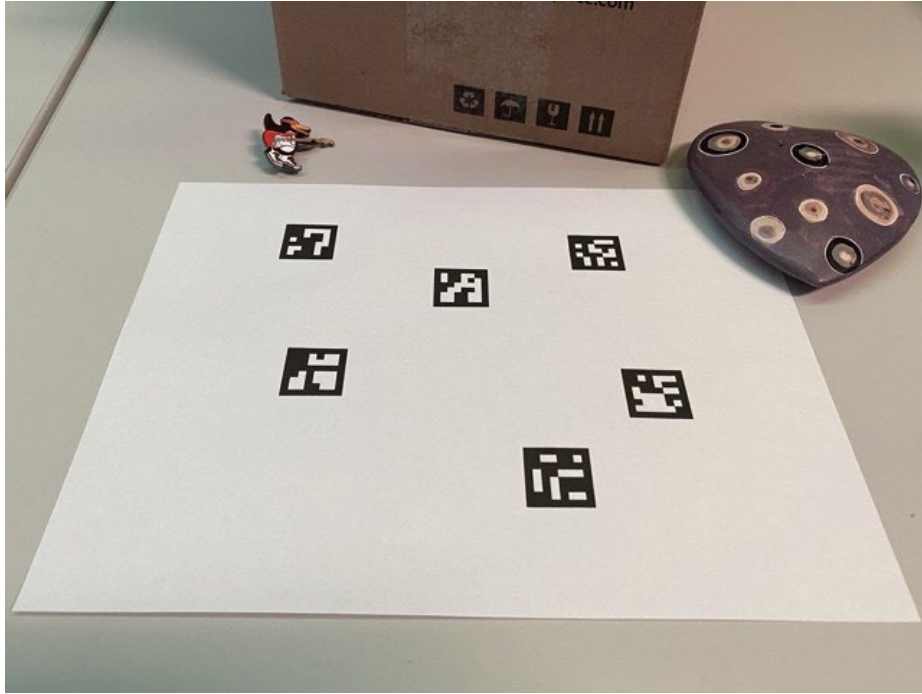


**Figure 15 Camera image containing ArUco markers [Garrido 2025].**

With edges detected, contours that do not resemble quadrilaterals are filtered out. By filtering out contours that are obviously not candidates, the processing required for candidate analysis is greatly reduced. Figure 16 shows the thresholded image with quadrilateral candidates marked.

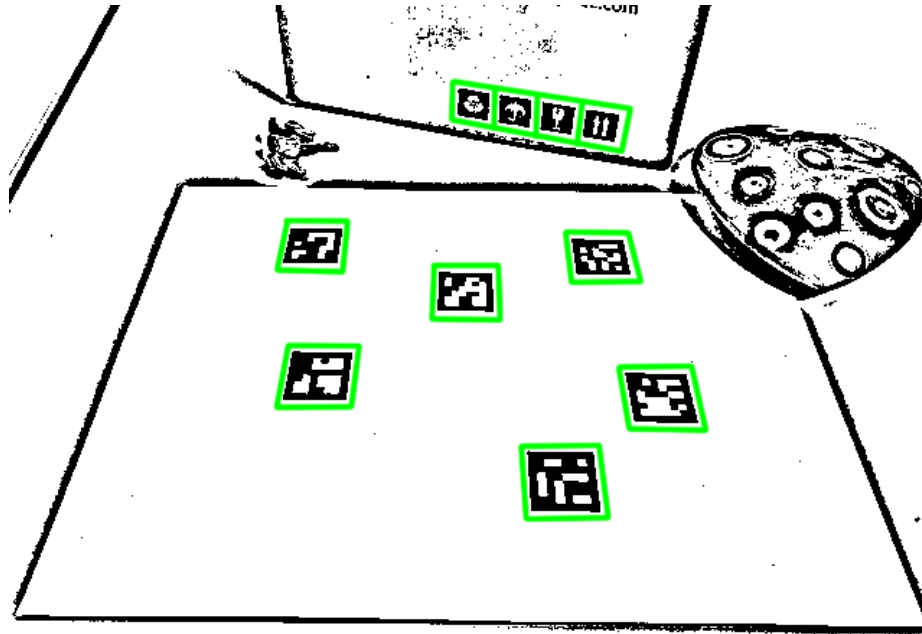


**Figure 16 Thresholded image with candidates marked. (Gamble 2025a)**

Markers may become occluded by debris during field operation, which raises the question: How much occlusion can the detection algorithm tolerate? An experiment aims to quantify the tolerable occlusion level.



**Figure 17 Perlin noise occlusion increasing from 10% coverage (left) to 50% coverage (right). (Gamble 2025a)**

Five ArUco markers, IDs 0 through 4 of the N5x5 M50 library, were studied. A Perlin noise generator was used to create various occlusion masks ranging from 10% occlusion to 50% occlusion (e.g. Figure 17). The occlusion masks were superposed on the ArUco markers and passed through the OpenCV ArUco detection algorithm. Two sets of occlusion masks were used: fine and coarse. The results show that as occlusion grain decreases, detection resiliency increases. In order to comprehensively quantify detection resiliency against occlusion, more grain sizes and markers would need to be analyzed.

These results are sufficient to show that it is important to characterize the expected occlusion grain size relative to marker size for a given application. For instance, HIVE testing has relied on markers in the range

of 45mm. If operating in a dry environment, occlusion due to dust and dirt could be expected to have grains of 1mm or less, following the fine grain results. If operating in a wet environment, occlusion due to mud splatter could be expected to have grains near 4mm, following the coarse grain results. That is, detection resiliency is likely worse in wet conditions than dry conditions. Detection resilience benefits from having larger markers, as it would not only reduce the relative occlusion grain size but also require more physical debris on the marker to reach the occlusion threshold where detection is disrupted.

## 4.5 Differential Drive Robot

A differential drive robot (DDR) is a wheeled robot that achieves 2 DOF movement without a dedicated steering mechanism. By avoiding the complexities of a steering assembly altogether, DDRs are very simple to construct as well as quite robust. Rather than a single drive axis and a steering mechanism as in a standard car, a DDR drives each of two wheels independently. This has the added benefit of giving the vehicle a zero-turn radius. Figure 18 illustrates the notation used in the kinematic Equation 3 and Equation 4, where:

$L$  = half-width of the vehicle [m]

$R$  = wheel radius [m]

$\phi$  = heading of the vehicle [rad]

$\omega_L$  = rotational velocity of the left wheel [rad/s]

$\omega_R$  = rotational velocity of the right wheel [rad/s]

$\omega$  = rotational velocity of the vehicle [rad/s]

$v$  = linear velocity of the vehicle [m/s]

$(x, y)$  = position of the vehicle [m]

The linear and rotational velocity are given by:

$$s = \frac{R}{2}(\omega_L + \omega_R)$$

**Equation 3. Linear velocity of differential drive**

$$\omega = \frac{R}{2L}(\omega_R - \omega_L)$$

**Equation 4. Angular velocity of differential drive**

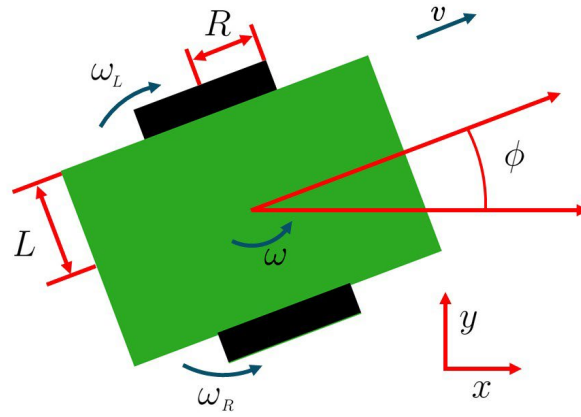


Figure 18 DDR notation. (Gamble 2025a)

## 4.6 Controller

In order to drive the DDR autonomously, a go to goal (GTG) controller is implemented. The GTG controller takes desired position as input. The GTG controller uses a nested loop design, as illustrated in Figure 19. The outer loop computes the necessary motor speeds to drive the DDR to the desired position. The inner loop computes the necessary voltages to achieve these motor speeds. More details on the DDR controller for the HIVE 3.0 can be found in (Gamble 2025a).

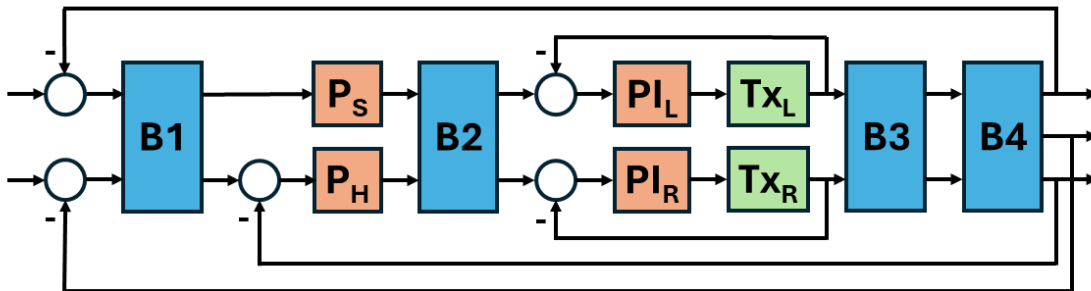


Figure 19 GTG controller block diagram. (Gamble 2025a)

## 4.7 Obstacles

The following is a discussion of a rudimentary obstacle detection algorithm that analyzes depth images to find obstacle edges, filters out surmountable obstacles, and outputs obstacles deemed insurmountable to an avoidance algorithm. The use of such an algorithm depends upon the degree of autonomy and human supervision of the HIVEs.

Obstacles, once detected, will be classified as either surmountable or insurmountable. Surmountable obstacles will be defined as those which can be driven over and need not be avoided. Insurmountable obstacles are those which cannot be driven over and must be driven around if possible. However, small culverts do not leave much room for avoidance due to their narrowness. If sufficient space exists between the obstacle and the wall of the culvert, the obstacle is passable, and the HIVE can advance around the obstacle. Otherwise, the obstacle is impassable, and the HIVE will remain in place. Figure 20 summarizes obstacle avoidance logic.

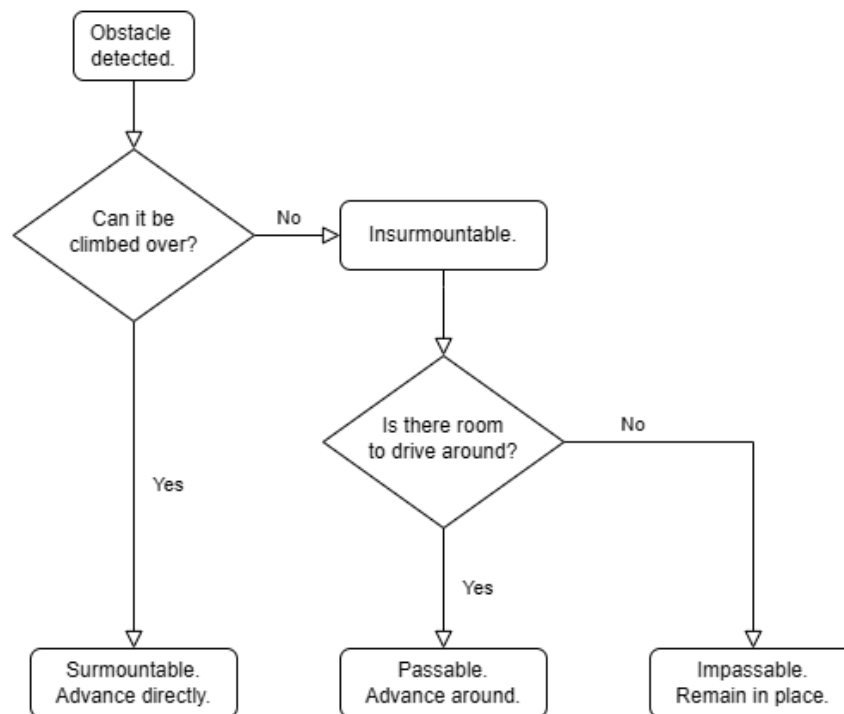


**Figure 20 Obstacle classification flowchart. (Gamble 2025a)**

*Detection* – The first stage of obstacle detection is horizontal edge detection. A vertical slice of the depth field through a cuboid obstacle manifests as in Figure 12: a line of near constant slope representing the ground gradually increasing in distance, then a corner at the bottom edge of the obstacle. Corners and jump discontinuities in the depth slice appear in the slope of the depth plot as local maxima, which can be detected using the SciPy Python library.

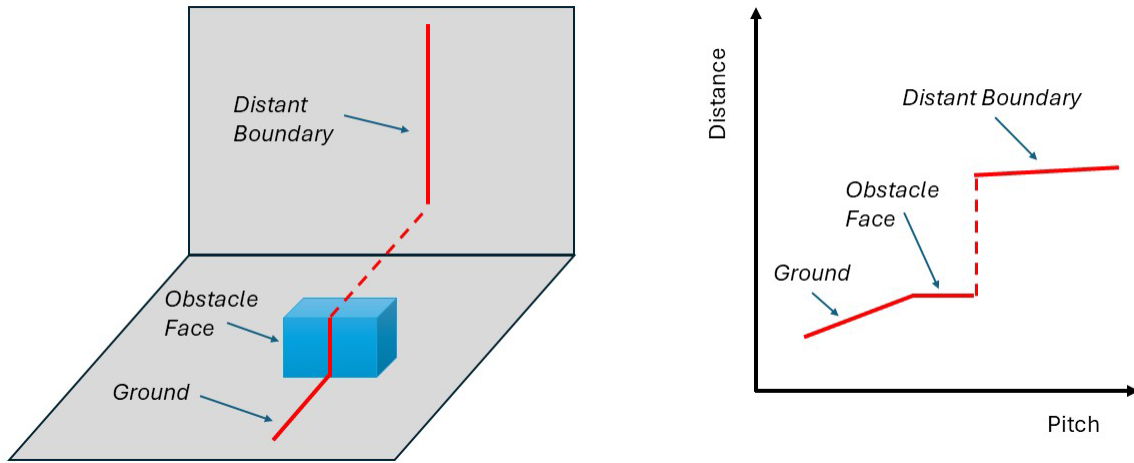


**Figure 21 Left: cuboid obstacle. Right: vertical depth slice of cuboid obstacle. (Gamble 2025a)**

With the polar coordinates of the obstacle edges identified, the obstacle can be analyzed for face length and angle as in Figure 22.

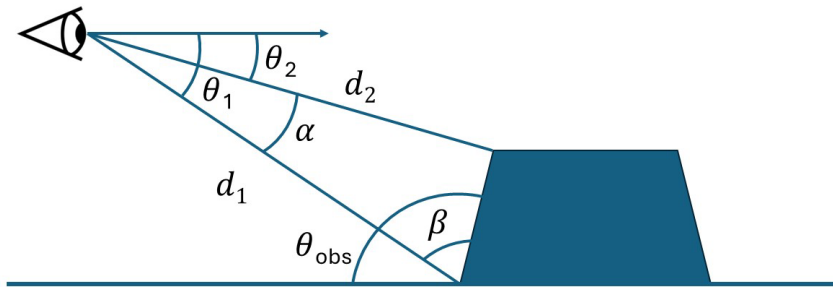


**Figure 22 Notation for obstacle analysis (Gamble 2025a)**

Successful application of the filter sequence to a set of candidate edge pairs returns true obstacle edge pairs of insurmountable obstacles. The filter sequence removes true obstacles that are surmountable and do not need to be avoided, such as small or low-angled obstacles. The final pairs that are returned define the contour of the obstacle and are passed to the obstacle avoidance algorithm.

*Avoidance* – Insurmountable obstacles are passed from the detection algorithm to the avoidance algorithm, which modifies the heading of the HIVE to steer around the obstacle. A common technique in path planning and obstacle avoidance is to treat the robot as a point in space, and then impose a safety radius, as in Figure 23. Once the desired heading has been computed, it is passed to the proportional heading controller.

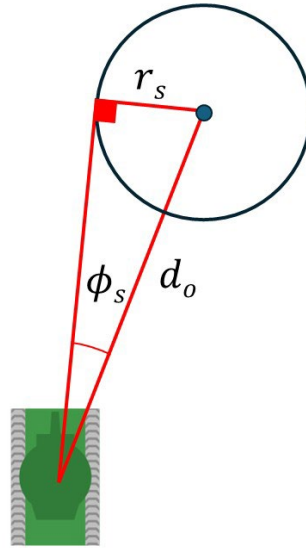


**Figure 23 Safety radius around point obstacle. (Gamble 2025a)**

Figure 24 shows the three cases possible for the relative target position.

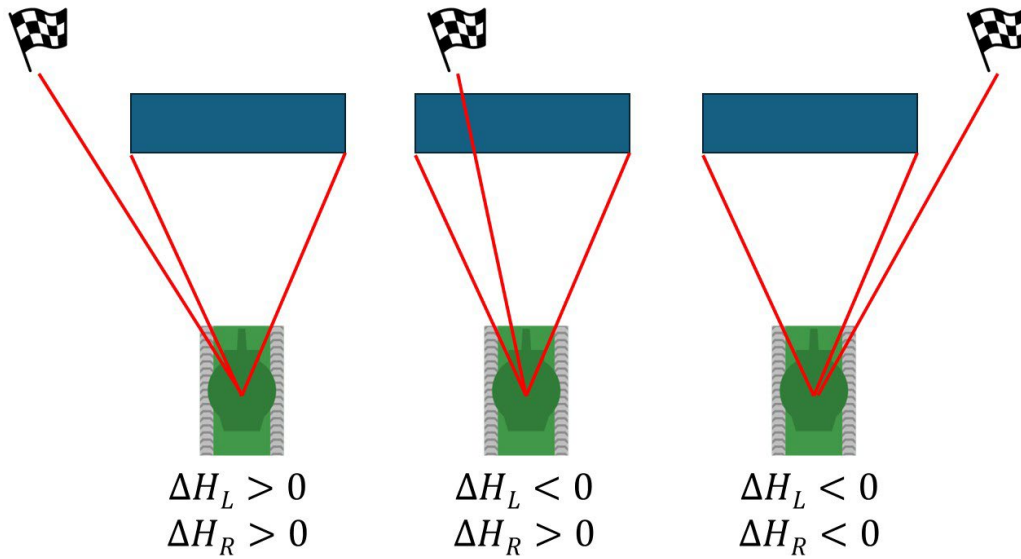


**Figure 24 Possible cases of target positioning relative to obstacle. (Gamble 2025a)**

Experiments to measure the precision with which obstacles can be detected and measured placed a cuboid obstacle in the foreground of the RealSense FOV. In the background stood a target with an ArUco

marker. When detected, the obstacle would be analyzed as described above. Figure 25 shows one instance of the depth field with obstacle and ArUco marker highlighted.

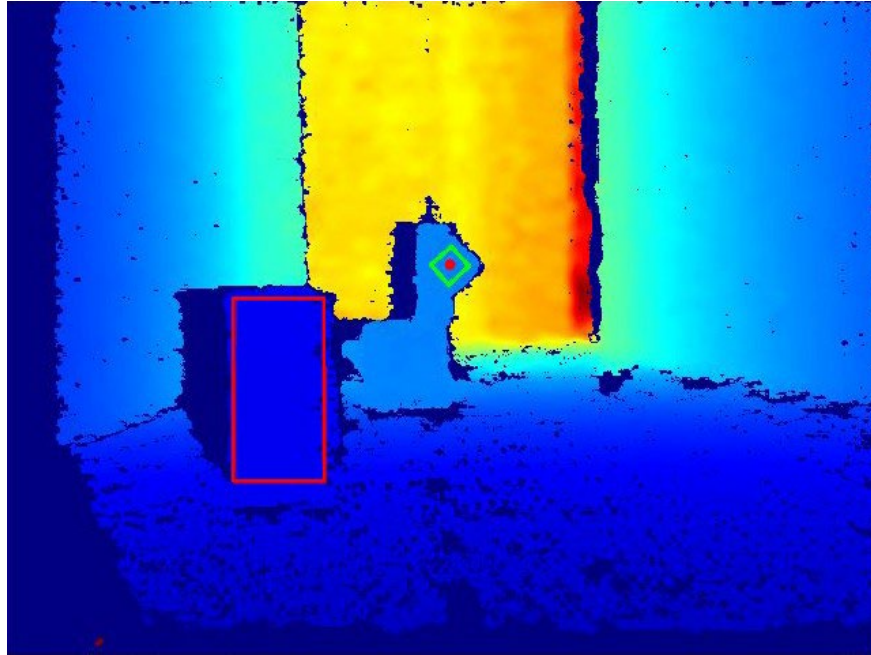


**Figure 25 Depth field with marker (green highlight) and obstacle (red highlight). (Gamble 2025a)**

The tests collected the following measurements for each obstacle: headings to lateral edges, distances to lateral edges, and face length. Each trial recorded 100 readings of each measurement. 15 trials were conducted with various obstacles placed in different locations and orientations. Headings of lateral edges (left and right) were combined into one category: heading. Distance was similarly combined, resulting in three metrics for detection precision: heading, distance, and face length. Figure 26 shows results from tests of obstacle detection parameters. The median error was -1.8% for heading, -1.6% for distance, and -2.1% for face length.

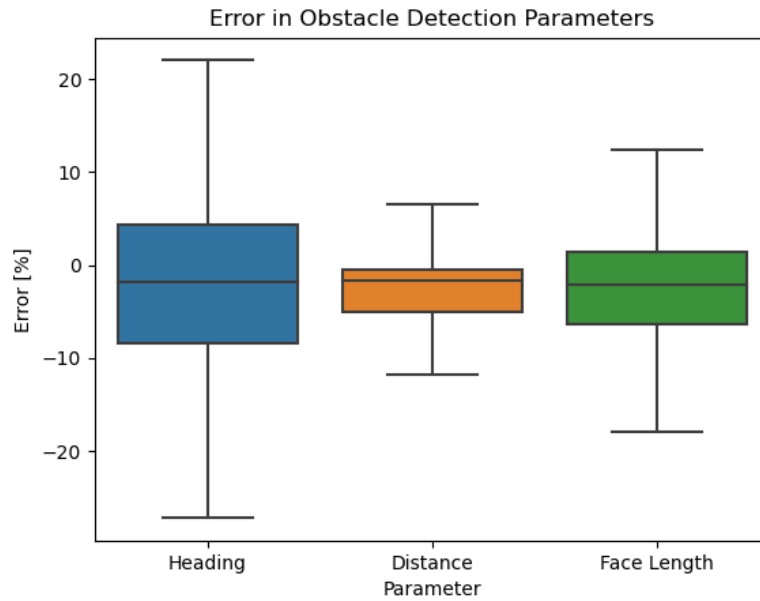


**Figure 26 Error in obstacle detection parameters. (Gamble 2025a)**

An error near to 2% across all obstacle measurements is more than sufficient for successful obstacle detection. A benefit of this analysis method for obstacles is that precision does not suffer in poor lighting owing to the IR dot matrix used by the RealSense. This is especially beneficial for culvert inspection where light is very limited.

Experiments to measure avoidance placed a cuboid obstacle between the HIVE and a target with an ArUco marker. The HIVE was then set to approach the target while avoiding obstacles. Various cuboid obstacles were placed in the direct path between the HIVE and the target.

Figure 27 shows from five trials avoiding an obstacle. The obstacle is successfully detected and maneuvered around without collision. An important limitation to this implementation of detection and avoidance is the small FOV of the RealSense, which is only 81°. Because of the limited FOV, the obstacle quickly goes out of view as it is passed and can no longer be detected. To avoid collision, the radius of expansion must be broadened. While the theoretical minimum for the expansion is the half-width of the tank, testing showed that an expansion less than the full width of the tank results in collision once the obstacle leaves the field of view but is still in proximity to the HIVE.

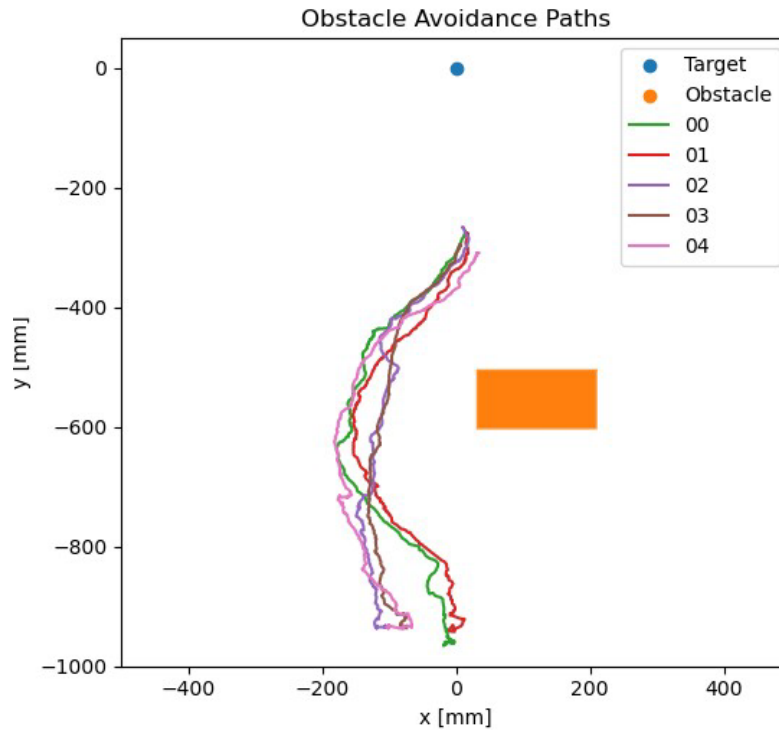


**Figure 27 Paths avoiding cuboid obstacle. (Gamble 2025a)**

## 4.8 Teaming

Multiple HIVEs can be deployed in a team using various architectures. Figure 28 illustrates three such teaming schemes. The most basic styles are parallel and serial. Parallel teaming can be applied in a scenario where grid-sweeping an area is required, such as collecting a large dataset of freeform scans in an open area in a GPR application. Serial teaming can be applied when telemetry range needs to be extended, as when inspecting culverts. These two teaming rules can be combined to create more complex teams. Followers can be programmed to follow or avoid specific ArUco IDs in order to configure a team architecture.

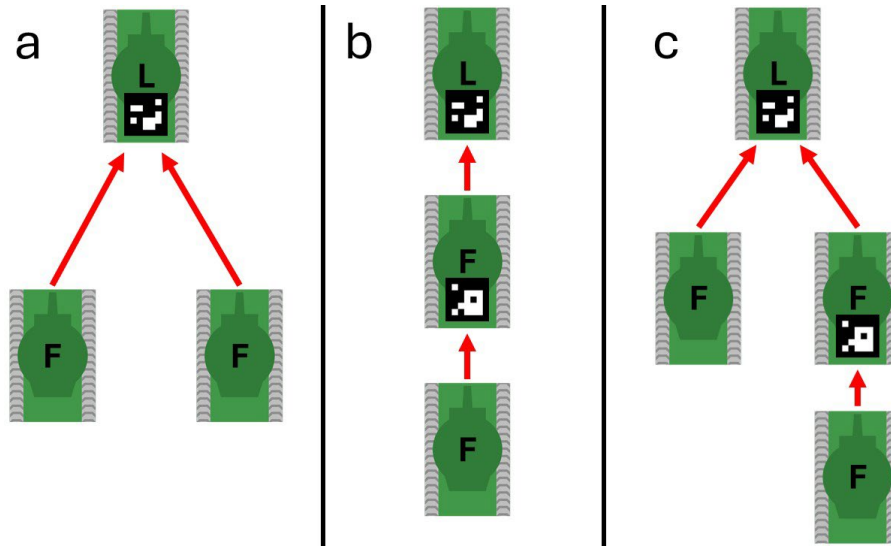


Figure 28 Various HIVE teaming schemes: a) parallel followers, b) serial followers, c) combined parallel and serial followers (Gamble 2025a)

## 4.9 Structural and Mechanical Modifications

**Shell with Integrated Camera Mount** – The top of the tank is replaced with a shell that is more robust and includes an integrated mount for the RealSense camera (Figure 29). The shell mounts to the tank using the same four screw holes of the original top. A bracket inside has holes that align to the two M3 bolt locations on the back of the RealSense camera.

**Rotary Encoder Housing** – An important modification to the structure of the tank replaces the glaucis plate with an integrated housing for the rotary encoders, which provide feedback for the control system. The housing holds the encoders such that they mesh with the exposed gears of the left and right gear trains (Figure 30), allowing tread speed to be measured.

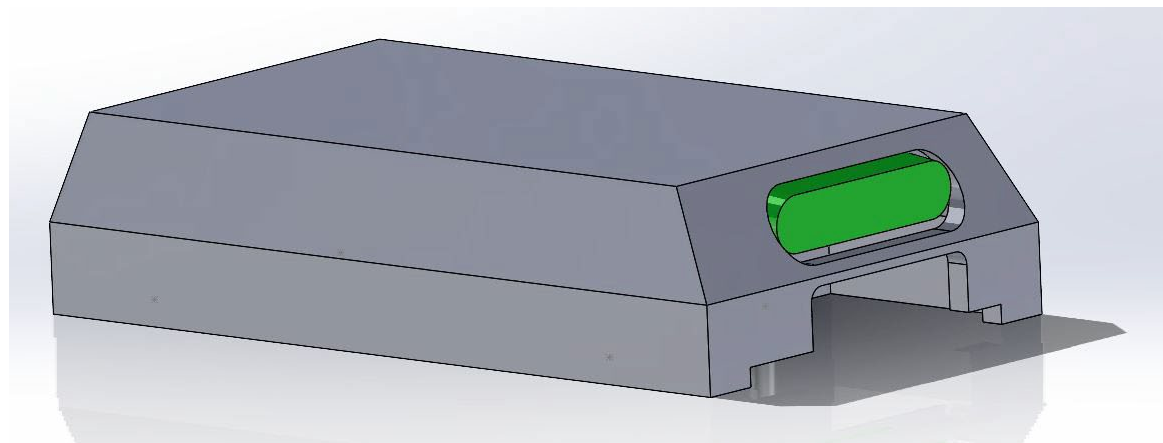


Figure 29 3D model of shell with camera mount (RealSense in green) (Gamble 2025a)

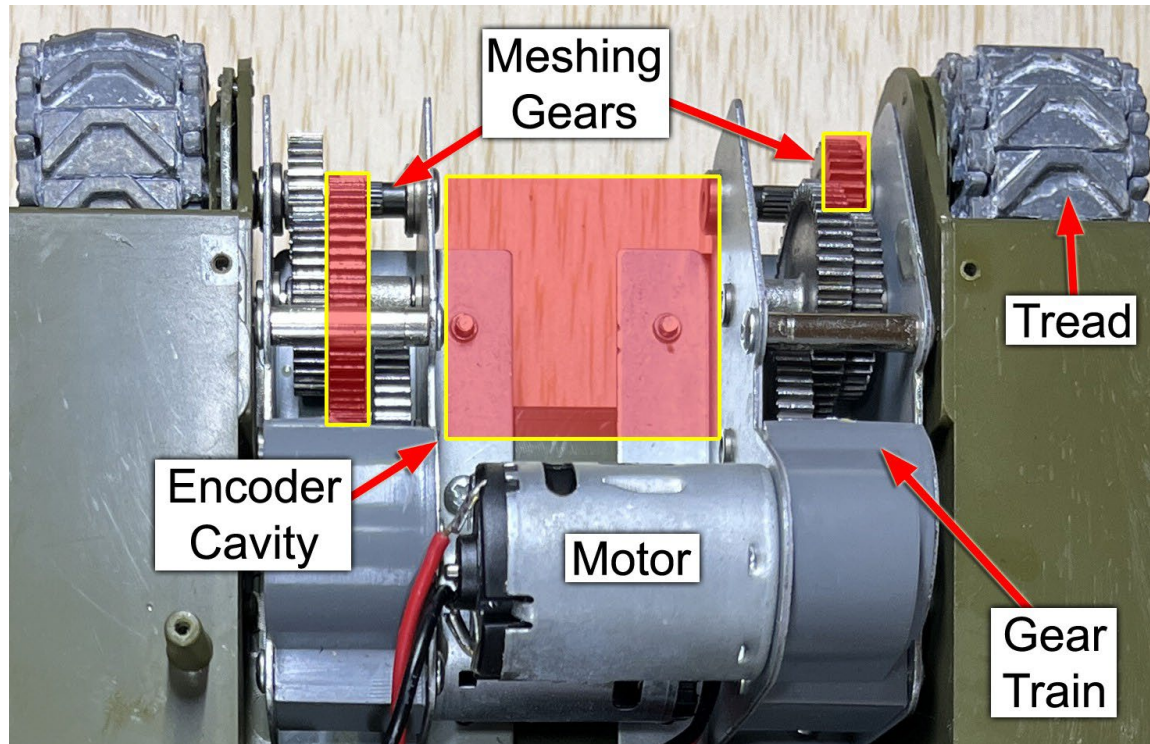


**Figure 30 Drive train components of Heng Long tank. Encoder mounting and meshing locations highlighted (Gamble 2025a).**

Before designing the encoder housing, a coupling gear must be selected to inform the positioning of the encoders for proper meshing. Gears based on metric dimensions with a module of 0.6 were selected. A 33T gear is selected for its small size, allowing it to fit into the compact gear train and position the encoders within the small cavity between the gear trains. The right encoder meshes directly with the 28T output gear (Figure 30), giving it a ratio of  $33/28 = 1.18$ . The left encoder is not able to mesh directly with the corresponding output gear due to geometry constraints on the positioning of the encoders in the small cavity between the gear trains. As such, it will mesh with the 53/40T compound gear (Figure 30), giving it a gear ratio of  $(33/53) \times (40/28) = 0.889$ .

Similar to the shell, the encoder housing (Figure 31) mounts to the tank using the same four holes of the original glasis plate. Each encoder mounting fin includes three bolt locations for fastening into the M3 threaded bolt holes atop the encoders.

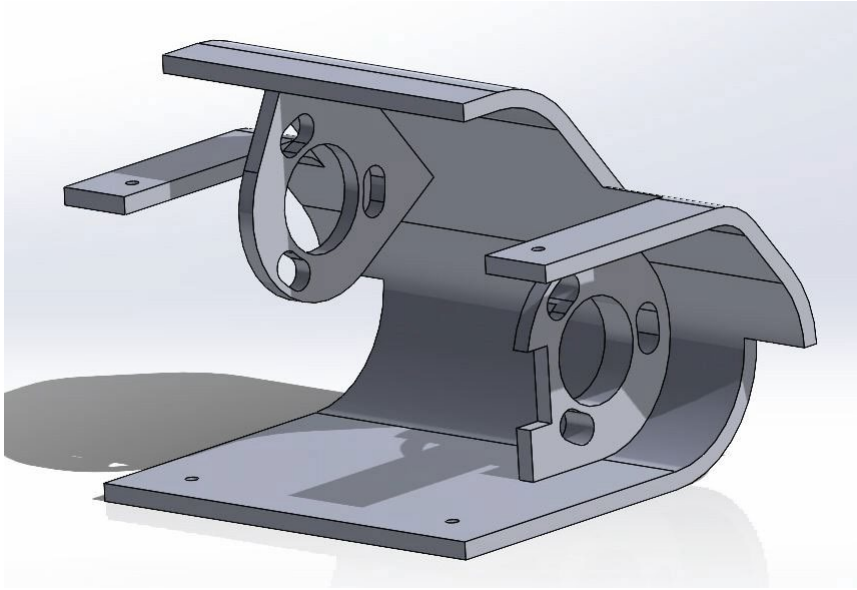


**Figure 31 3D model of encoder housing (Gamble 2025a)**

#### **4.10 Low-Cost Motor Actuator (LCMA)**

The Heng Long Sherman tank comes standard with a TK-7.0 or TK-7.1 control board (Figure 32). It has nearly 20 inputs and outputs, but most of its functionality is dedicated to lights and sounds. The HIVE 3.0 replaces the TK-7x with a custom motor control board, the LCMA, which has increased control and communication functionality.

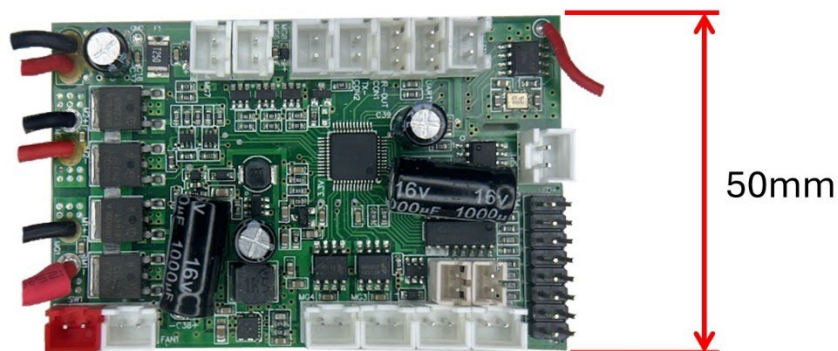


**Figure 32 Heng Long TK-7.0 Tank Function Main Board. (Gamble 2025a)**

The LCMA (Figure 33) utilizes three integrated circuits to handle the main tasks: power distribution, control feedback, and serial communication. Power is distributed to the motors by the TB6612FNG. Feedback is captured from the two rotary encoders to monitor tread speed. Two-way serial

communication is achieved via USB using the FT232RL or directly with the UART pins. The board is easily adaptable to any differential drive vehicle by changing a few software parameters.

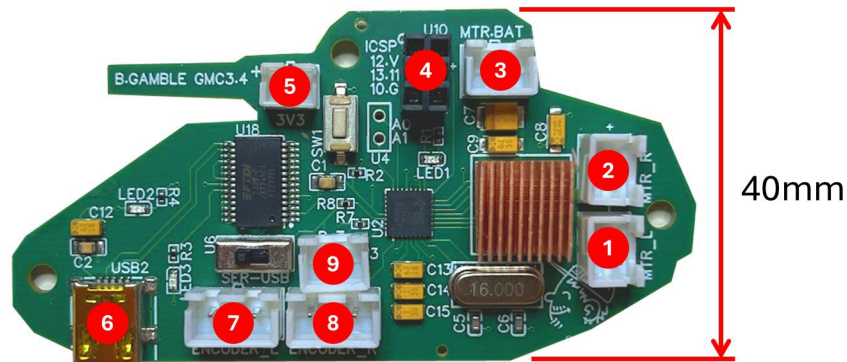


**Figure 33 LCMA with connectors numbered. (Gamble 2025a)**

The tech-package includes software for two operating modes, speed control and throttle control, but can be programmed with any control logic. In speed control, the board accepts motor speed setpoints via serial communication. A PI controller determines the motor voltages needed to track the setpoints. Speed control mode is used for followers. In throttle control, the user controls the motor voltages directly and is used for the leader.

Connectors – All connectors on the board are labeled on the silkscreen for convenient reference. Figure 33 shows the connectors, numbered counterclockwise starting from the right edge as viewed from the top.

#### 4.11 AMB Relay

Video is transmitted using two AMB82-mini modules as illustrated in Figure 34, where the distal AMB transmits its signal to the proximal AMB. The proximal AMB transmits both its own signal and the distal AMB signal to the PC for the operator to view both video streams simultaneously. The video signals are transmitted and streamed via a WiFi network hosted locally by the proximal AMB module.

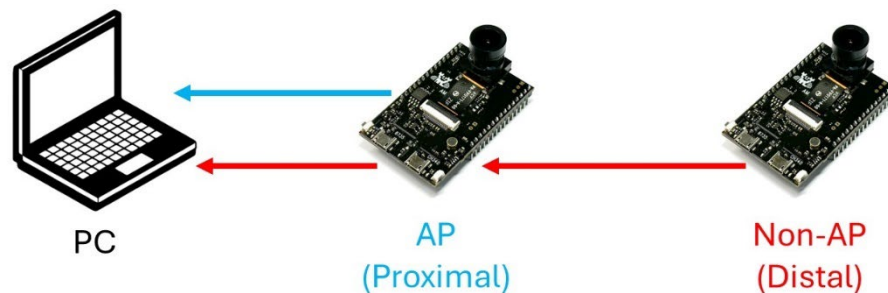


**Figure 34 Video signal relay network with AMB82-mini modules. (Gamble 2025a)**

## 4.12 HIVE 3.0 System Testing and Results

The following sections present and discuss the results of various tests on the subsystems of the HIVE as well as a fully integrated system test.

**Depth Estimation** – Depth estimation methods were evaluated and compared for three methods: 1. Stereoscopic depth estimation with a RealSense D435i; 2. Object of known size – trigonometric; and 3. Object of known size – calibration. A 45mm target was placed in front of the sensors in 100mm increments from 200mm to 1500mm. At each distance, 100 estimations of target distance were collected. The results of all three methods of depth estimation are superposed in Figure 35. The RealSense is the best depth estimator, with the lowest maximum median error of just 1.7%, maximum IQR of 0.3%, and no well-defined relationship between target distance and median error. Next is the calibrated trigonometric approximator, with a maximum median error of -2.8% but much higher variance in error than the RealSense, with a maximum IQR of 4.8%. Finally, the pure trigonometric approximator, with a maximum median error of 6.3% and maximum IQR of 5.4%.

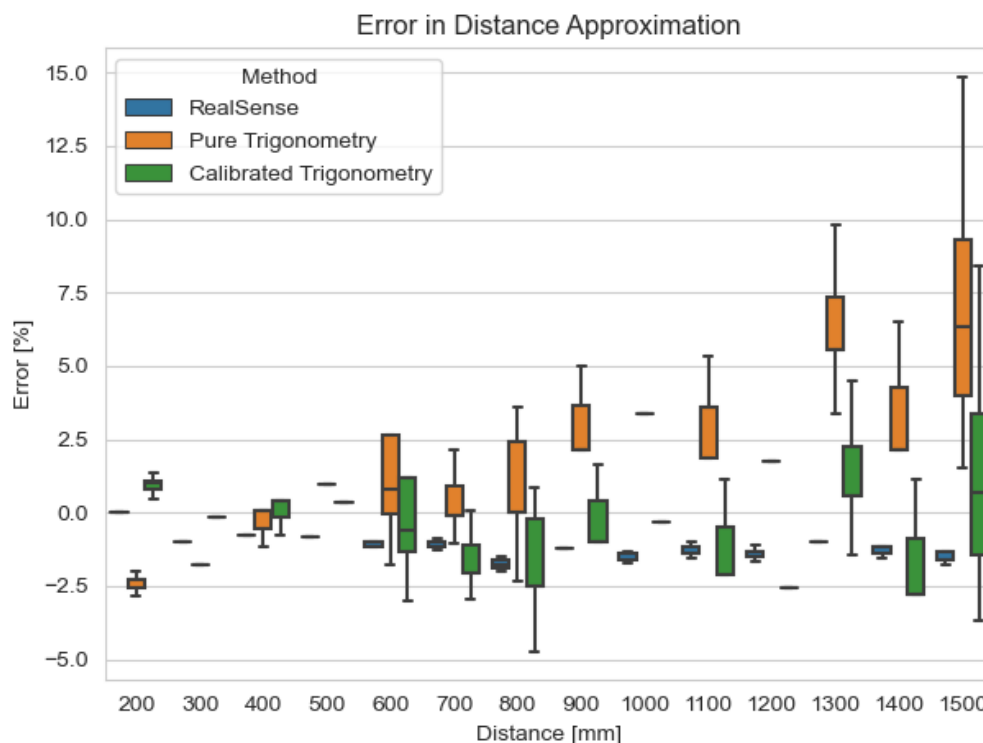


**Figure 35 Comparison of depth estimation techniques (Gamble 2025a)**

**Target Tracking (Outer Loop Controller)** – Similar to the inner loop, the outer loop is tested and tuned in stages. The first stage isolates heading and distance tracking, tuning independently. Next, the full GTG algorithm is tested by enabling both heading and distance tracking simultaneously, observing how they interact with each other, and deciding if adjustments need to be made.

While the inner loop was tuned to be fast (on the order of 100 ms), fast tracking is undesirable for the outer loop, as it caused jerky movements of the tank. The goal of tuning the outer loop is to have settling times near 2-3 seconds to ensure steady, smooth movement of the tank. Using less aggressive gains and throttling the maximum linear and rotational speeds of the tank helps to achieve this goal. All outer loop testing used inner loop gains  $K_P=1$  and  $K_I=0.08$ , as selected previously.

*Heading Tracking* – For tracking heading, two step sizes of 10 and 40 degrees were tested. The RealSense aligned-FOV is 42 degrees, making 40 just under the maximum possible test value.  $K_h=1$  gives poor results, with no actuation effort in the small step and a steady state error of 34.6% in the large step. Increasing to  $K_h=6$  achieves sufficient steady state tracking with 8.06% and 0.348% steady state error in the small and large steps, respectively, along with stall times less than two seconds. Gains greater than 6, introduce significant overshoot: 50% in the small step and enough in the large step that the target left the field of view of the HIVE (see  $K_h=10$ , 1.5s, where heading jumps to zero at point when target is no longer registered). With near sufficient steady state tracking, a settling time just under 2s for both the small and large steps, and no overshoot,  $K_h=6$  is selected as the heading gain.

*Distance Tracking* – The results of distance tracking tests found that the small step,  $K_s=0.002$  has the best response, with settling time of 2.15s and no overshoot. However, in the large step  $K_s=0.002$  has a significant 18.4% overshoot. Lowering the gain to 0.0015 reduces the overshoot to 9.87% in the large step, with no overshoot in the small step. Settling times for step sizes are about 3s, which is sufficient. Therefore,  $K_s=0.0020$  is selected as the speed gain.

*Go-To-Goal (GTG)* – The operator is shown four video feeds during testing (Figure 36): the leader view (L) and three follower views. The first follower view (F1) is the raw RGB feed. The second (F2) is the RGB feed aligned to the depth feed with tracking visuals overlaid. The third (F3) is the depth feed with tracking visuals overlaid.

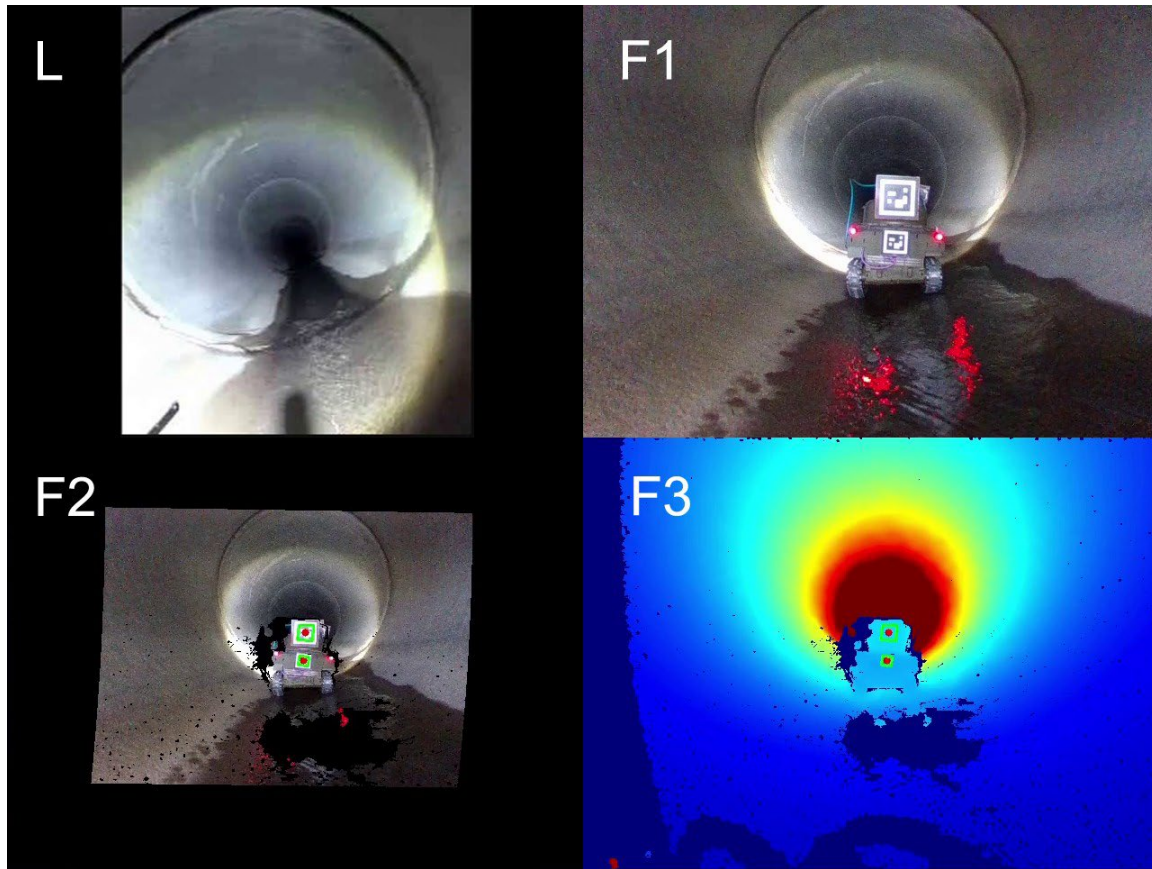


**Figure 36 Culvert inspection video feeds: L) leader view, F1) follower view, F2) follower view aligned to depth, F3) follower depth view (Gamble 2025a)**

### 4.13 Signal Transmission

*Control Signal* – XBee S2C modules transmit the control signal in a relay: one coordinator with three relays communicating at 2.4GHz. The manufacturer claims 1200m open-air transmission range.

Performance testing consisted of three phases, as illustrated in Figure 37. In the initial phase a HIVE, the remote, and two relay nodes are powered on in proximity to one another and a relay network is established. The HIVE is attached to a spooled tether and an open reel tape measure. In the first phase, the HIVE is driven away until signal is lost. It is then reeled back into range, and a relay node is fixed to the tether. The second and third phases repeat this network extension process. Transmission distance was tested in open-air, a 36in concrete culvert, and a 24in HDPE culvert.

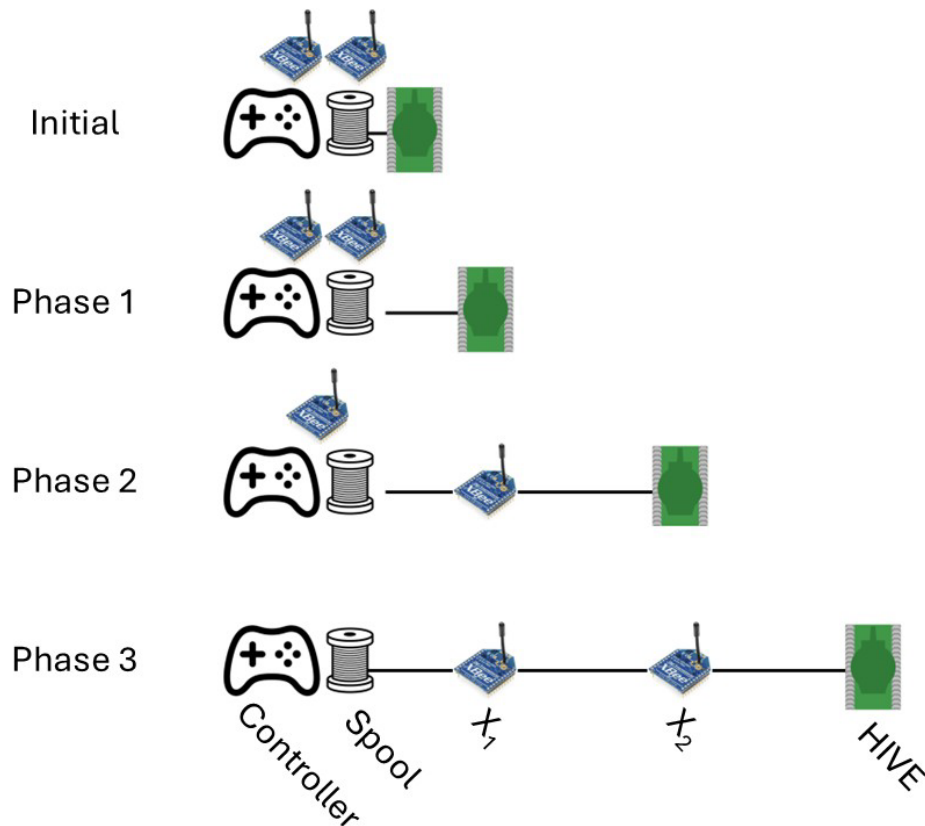


**Figure 37 Control signal transmission distance test phases (Gamble 2025a)**

Maximum control signal transmission ranges for the test environments are given in Table 6. Maximum open-air node spacing was 31.91m – only 2.7% of the range claimed by the manufacturer. It is not clear under what conditions and configuration 1200m transmission range is possible.

In the 36-in concrete culvert, control signal was still being received when the HIVE reached the end of the culvert at 48.78m (16.26m node spacing). With the control signal still being received strongly, greater range was possible.

In the 24-in HDPE culvert, the signal was lost as the HIVE reached the end of the culvert at 45.72m (15.24m node spacing). Once retrieved, the HIVE was found to have water inside the body, and the electronics were powered down. It is likely that water ingress caused the electronics to shut off before maximum signal range was reached.

While the maximum individual node spacing for the XBee modules is less than the stock remote range (~50m), the benefit of the XBee modules is their relay capacity. Hundreds of XBee units can be strung into a relay network to provide the desired transmission range. Furthermore, the XBee relay strategy enables corner-transmission, and the use of IOT-type transponders, which is not possible with the stock remote, greatly increasing inspection capability.

**Table 6 Control signal inter-node transmission range (four nodes in network).**

| Test Environment1     | Node Spacing [m] |
|-----------------------|------------------|
| Open-air              | 31.91            |
| 36in concrete culvert | >16.26           |
| 24in HDPE culvert     | 15.24            |

*Video Signal* – AMB82-minis transmit the video signal. These are dual-band devices capable of using 2.4 and 5 GHz frequencies. All tests used 5GHz Wi-Fi for communication in a three-node network. One AMB acts as an access point, hosting a local Wi-Fi network to transmit data. A distal AMB connects to this network to stream its video signal. A PC connects to the access point AMB via the local Wi-Fi network and is able to stream both video signals.

Similar to the control signal testing, video signal transmission was tested in open air, a 36in concrete culvert, and a 24in HDPE culvert. However, because the AMBs have much greater transmission range, a different method was used, as illustrated in Figure 38 the AMB access point was attached to a HIVE and driven away from the PC and distal AMB, which stayed together with the operator. The video stream of the distal AMB, despite being directly next to the PC, is only accessible via the access point.

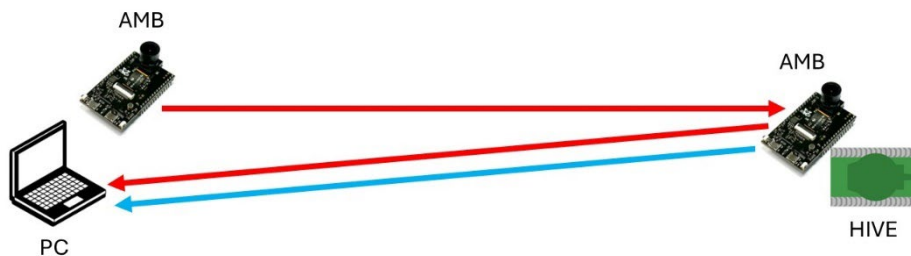


**Figure 38 Video signal transmission distance test diagram (Gamble 2025a)**

Maximum video signal transmission ranges for various test environments are given in Table 7. For the three-node network tested, maximum observed node spacing was 300m in open-air, 48.78m in the 36in concrete culvert, and 45.72m in the 24in HDPE culvert. The signal was never lost in any test: maximum transmission range of the AMB modules was not observed in any test scenario. Their performance well exceeds that which is needed for culvert inspection. Figure 39 shows a still image of the video signal from the lead HIVE near the end of the 24in HDPE culvert. One drawback to the AMBs is that they are not well suited for adding additional nodes to the network.

**Table 7 Video signal inter-node transmission range (three nodes in network).**

| Test Environment2     | Node Spacing [m] |
|-----------------------|------------------|
| Open-air              | >300             |
| 36in concrete culvert | >48.78           |
| 24in HDPE culvert     | >45.72           |

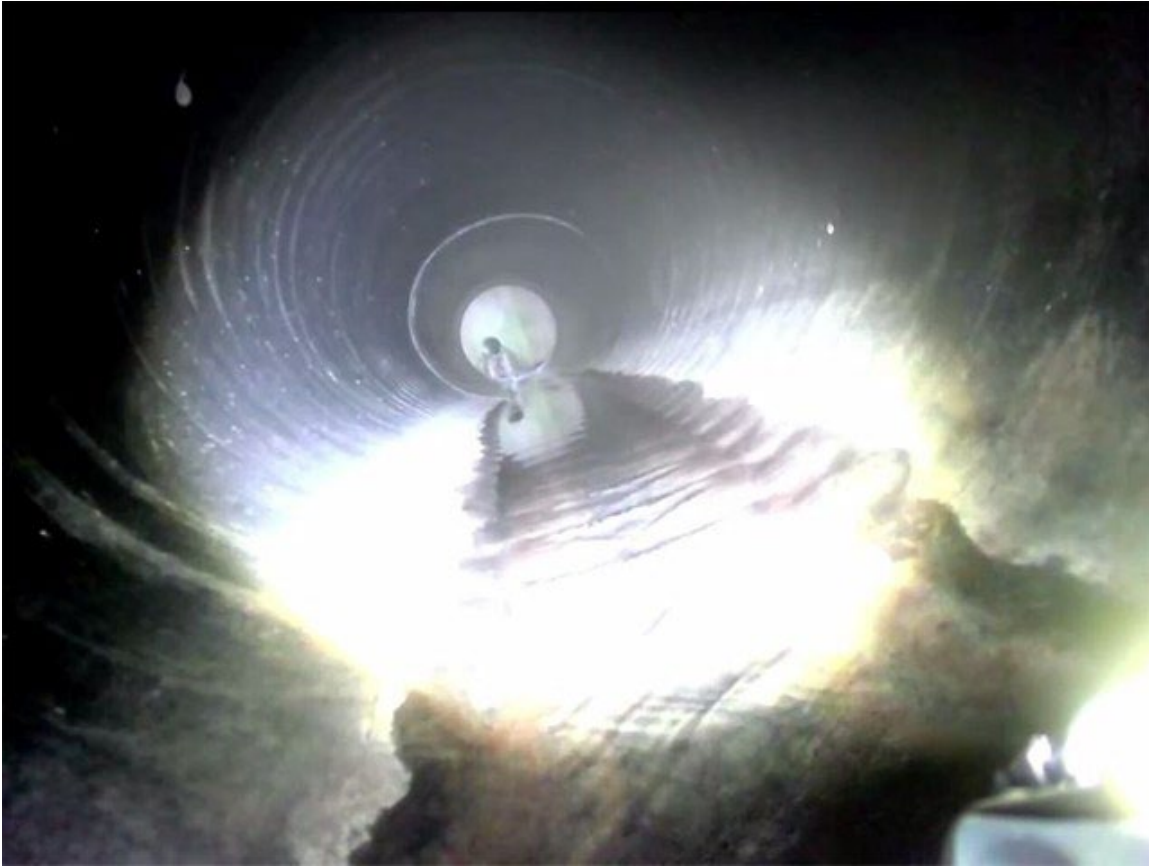


**Figure 39 Leader FOV in 24in HDPE culvert with drop-inlet junction visible at end of culvert (Gamble 2025a)**

#### **4.14 Further Cost Reductions**

*Chassis* – A critical design consideration of HIVEs is keeping the system low-cost. The most expensive standard component of the HIVE 3.0 is the Heng Long tank, at \$229.99. The HIVE 2.0 relied on the Heng Long tank not only for its chassis and drivetrain, but more importantly its control electronics. The HIVE 3.0, however, strips the tank completely down to its chassis and drivetrain, replacing the control electronics with an LCMA. Therefore, it is suggested that future designs transition from the Heng Long tank to a generic clean tank chassis kit, which can be purchased in the range of \$100. Replacing the Heng Long with a metal chassis would not only result in a more robust vehicle, but also reduces the price by over \$100, bringing the cost of a leader down to just \$295.80. This switch in chassis inspired part of the HIVE 4.0 design.

*Depth* – An alternative to the RealSense is a 360° LiDAR scanner, which can be purchased in the range of \$100. This would both reduce the cost of the smart-follower as well as increase obstacle detection and avoidance performance.

*Signal Transmission* – As previously discussed, the AMB far outperforms the XBee in data transmission. This could be due to factors such as antenna design, transmission power, transmission, frequency, or software. It may be beneficial to migrate the control signal transmission away from XBees to the AMB. This would simplify the system, using less components. However, one drawback of this is the difficulty in increasing the AMB network to greater than 3 nodes.

## Chapter 5. Culvert Inspection Intelligent Assistance Systems

*Requirements* – The quality and efficiency of the inspection can be improved with automated defect identification, localization and assessment methods implemented in software. As long as the software is not too compute heavy, this does not add any complications to the process of physically building the inspection robot. Computational resources are probably not a big constraint because these assistance systems are primarily focused on being used as a post-data processing approach on the PC rather than implementing it in real-time. An initial focus is assessment of culvert joint gaps. The width of the gap should be less than 6 inches. The width of this gap will be estimated from the top camera feed.

*Method* – The overall techniques is:

- (a) Camera Calibration: The video feed is corrected for camera lens distortion.
- (b) Edge Detection and Curve-Fit: The gap's two boundaries (edges) are detected, followed by fitting a curve and then finding the average distance between the two curves.
- (c) Locating the joint gap defect

Details follow.

*Camera Calibration* – The standard method of intrinsic camera calibration - using checkerboards is performed using the cameraCalibrator app on the MATLAB computer vision toolbox as shown in Figure-6(a). The intrinsic camera parameters are extracted from this process to a mat file, which undistorts the images of joint gaps from the top camera (Fetic 2012).

*Edge Detection and Curve-Fit* – The images are quite noisy and pixelated at times depending on the distance between the robot from the inlet of the culvert. A comparative analysis of different edge detection filters - Sobel, Prewitt, Laplacian, and Canny is performed on a sample image of the gap using both RGB and Grayscale image as the input for the filter on MATLAB as shown in Figure 40.b. From this comparison, Sobel and Prewitt edge detection filters performed better with no big difference between an RGB or a Grayscale image. So, the general procedure of converting the RGB to a Grayscale image and applying the kernel over the Grayscale image is used. Sobel provides further improvements in the edge detection pipeline because there is a good probability that the gap of interest is in the center of the picture, which the Sobel filter emphasizes more, (Sobel 1968).

The code flow is: First, the image is loaded and converted to Grayscale to simplify processing. A median filter then minimizes noise, followed by a Gaussian filter that smooths out the image. The Sobel method detects edges in the smoothed image, followed by morphological procedures with the 'strel' function of MATLAB, that clean up the edges and close minor gaps. Contours of detected edges are identified, and tiny contours are filtered out by fixing a threshold contour length decided upon observation along with trial and error. The original image is presented with the detected contours overlayed, and the discovered edge coordinates are taken for curve fitting.

*Locating the Joint Gap Defect* – As discussed earlier in the spool design section, we can get the distance vs time feed from the spool system. From the video feed, we can get the image frame versus time. Thereby, if a frame with a defect is detected, the timestamp of that defect can be obtained; using these two feeds determines an approximate location of the defect.

Requirement for a Better Framework – It should be noted that the above approach is just the starting point of the culvert inspection assistance system and is rule-based, with considerable room for improvement.

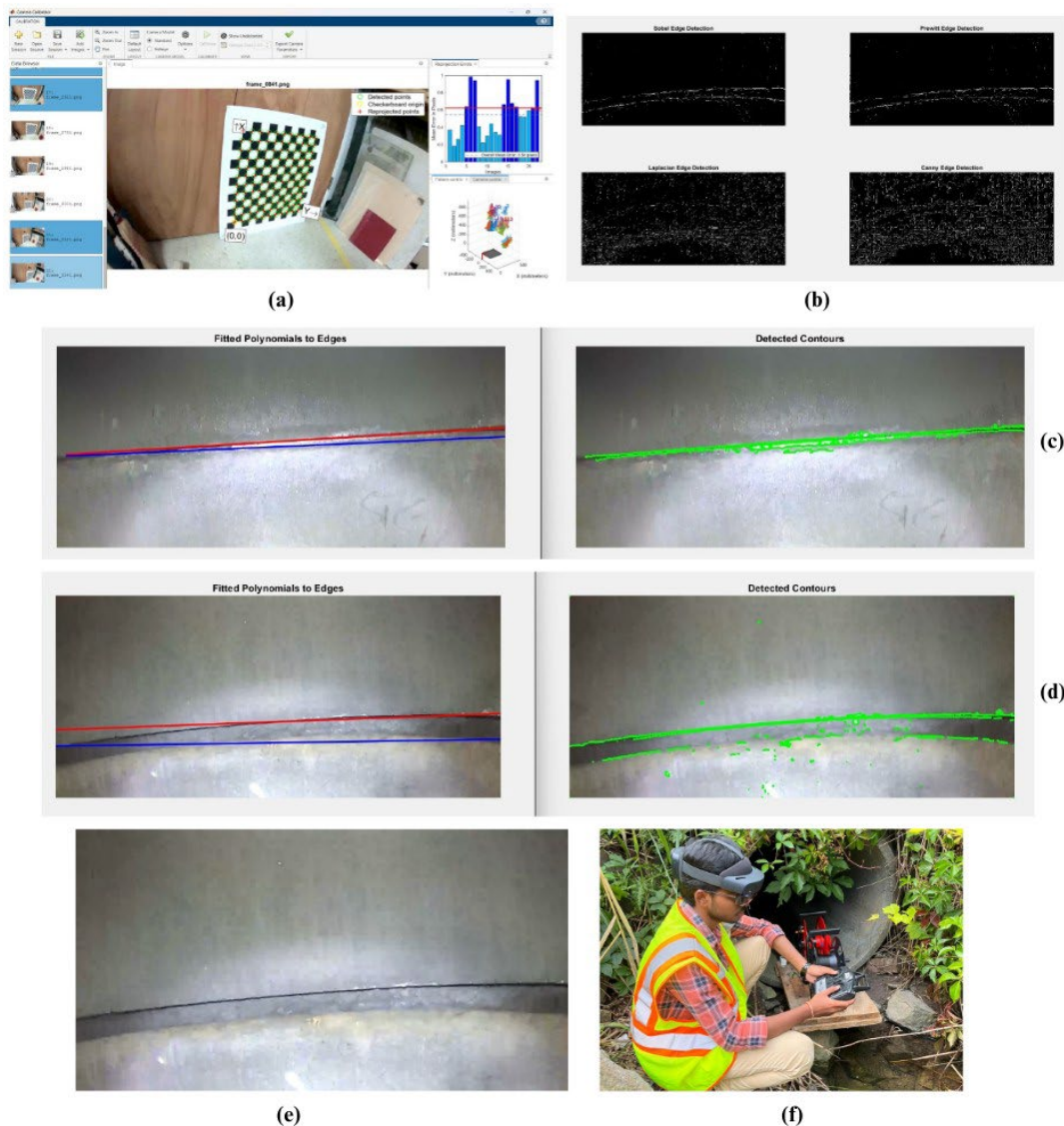


**Figure 40 (a) Checkerboard-based camera calibration on MATLAB camera Calibrator (b) Comparative analysis of different edge detection algorithms (c) Edge detection and contour fit for a normal case of culvert joint (d) Edge detection and contour fit for a case with a larger gap, not defective - the gap was approximately 2 inches (e) Image frame of the gap from the video feed of the top camera (f) Inspection using AR headset (Microsoft HoloLens 2)**

Implementing a robust framework could start by trying CNN architectures using LabelMe software or a random forest classifier, focusing on different categories of defects that will be examined across various types of culverts. Depending on the results, a more sophisticated network can be selected. Mohammadi has evaluated multiple architecture implementations in his research (Mohammadi 2023) and concluded

that RF performs with better accuracy; this would be useful in building assistance frameworks after data availability. 3D reconstruction of the culvert will make the inspection procedure efficient and comfortable, if possible, without adding extra hardware and complicating the physical system (Xue 2022).

Augmented reality (AR) is another potential inspection assistance system. Instead of looking at the camera feed with less clarity with the brightness and lighting under the sun, one could use an AR headset and connect it to the IP address of the camera to inspect the feed as shown in Figure 40.f. AR may make the inspector's job easier (Fath 2023)(Wang 2019) (Mascarenas 2021).

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## Appendix A: HIVE 2.1 Build Instructions

Building a HIVE 2.1 requires a Heng Long M4A3 RC tank with TK7.0 main board as the primary chassis. The steel treads and metal drivetrain are recommended options. It is required to acquire the additional parts as listed in Table 8 .

**Table 8 HIVE 2.1 parts list (prices from December 2025)**

|                                                             |     |                                                                                                                                                                                         |          |
|-------------------------------------------------------------|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| Tank - Chassis,<br>Wireless Controller,<br>Battery, Charger | 1   | <a href="https://www.amazon.com/dp/B07BFGT9P5">https://www.amazon.com/dp/B07BFGT9P5</a>                                                                                                 | \$229.99 |
| Power Cable                                                 | 1   | <a href="https://www.amazon.com/dp/B0DF2JQXWN">https://www.amazon.com/dp/B0DF2JQXWN</a>                                                                                                 | \$0.28   |
| Lever Wire<br>Connectors                                    | 1   | <a href="https://www.amazon.com/dp/B0CMTH85QG">https://www.amazon.com/dp/B0CMTH85QG</a>                                                                                                 | \$0.93   |
| Headlamp                                                    | 1   | <a href="https://www.amazon.com/dp/B07WP393CS">https://www.amazon.com/dp/B07WP393CS</a>                                                                                                 | \$8.50   |
| Turret                                                      | 1   | Custom 3D print                                                                                                                                                                         | N/A      |
| AMB82                                                       | 2   | <a href="https://www.digikey.com/en/products/detail/seed-technology-co-ltd/102991774/17775364">https://www.digikey.com/en/products/detail/seed-technology-co-ltd/102991774/17775364</a> | \$49.98  |
| SD Cards (Qty 2)                                            | 2   | <a href="https://www.amazon.com/dp/B08TJTB8XS">https://www.amazon.com/dp/B08TJTB8XS</a>                                                                                                 | \$15.54  |
| 90 degree USB (Qty 2)                                       | 2   | <a href="https://www.amazon.com/STUPDOLERI-Female-Extension-Connector-Adapter/dp/B0CSK1648C">https://www.amazon.com/STUPDOLERI-Female-Extension-Connector-Adapter/dp/B0CSK1648C</a>     | \$9.99   |
| Red Reel                                                    | 1   | <a href="https://www.amazon.com/dp/B000E8SWQM">https://www.amazon.com/dp/B000E8SWQM</a>                                                                                                 | \$17.55  |
| Magnet Counter                                              | 1   | <a href="https://www.amazon.com/dp/B01DNLRAUA">https://www.amazon.com/dp/B01DNLRAUA</a>                                                                                                 | \$13.99  |
| Wire Spool and<br>Crimps                                    | 1   | <a href="https://www.amazon.com/dp/B0DP26W544">https://www.amazon.com/dp/B0DP26W544</a>                                                                                                 | \$18.99  |
| Carabiner                                                   | 1   | <a href="https://www.amazon.com/dp/B073TL6RSJ">https://www.amazon.com/dp/B073TL6RSJ</a>                                                                                                 | \$2.41   |
| Superglue                                                   | 1   | <a href="https://www.amazon.com/dp/B0DMJGM2TT">https://www.amazon.com/dp/B0DMJGM2TT</a>                                                                                                 | \$0.34   |
| Polyurethane<br>Waterproofing                               | 1   | <a href="https://www.amazon.com/dp/B06XC3JBVJ">https://www.amazon.com/dp/B06XC3JBVJ</a>                                                                                                 | \$39.86  |
| Corrosion X<br>Waterproofing                                | 1   | <a href="https://www.amazon.com/dp/B0009H1AMG">https://www.amazon.com/dp/B0009H1AMG</a>                                                                                                 | \$26.95  |
| Total                                                       | N/A | N/A                                                                                                                                                                                     | \$435.30 |

It is also required to 3D print a set of custom plastic parts for the reel assembly. 3D printing files can be accessed at

[Parts files for 3D printing](#)

## A.1 Turret Instructions

### Step 1: Attach Camera to AMB Board

An AMB 82 board is pictured in Figure 41. Two are used in the building of the HIVE and are extremely important for its functionality. The process of attaching the cameras to the AMB boards can be quite tricky and tend to detach with sufficient pressure. If during the construction of the turret the cameras become detached from the board, you can work with the following instructions to secure the connection.

Slide the ribbon cable into the open slot. If the slot is open, the grey covering should be positioned vertically as shown in the left photo. Once the ribbon cable is inserted into the opening, snap the grey covering shut as pictured in the right photo. The camera should now be securely attached to the board.

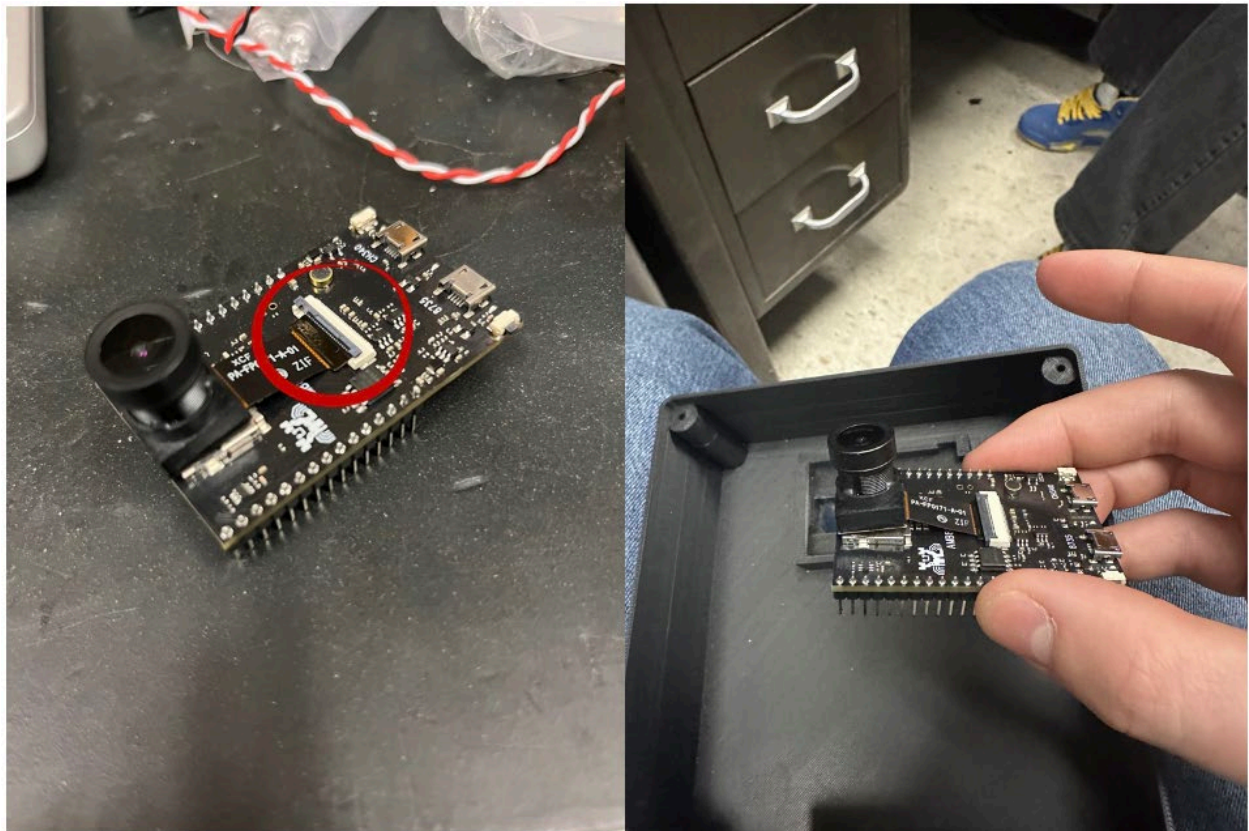


Figure 41 Attach Camera to AMB 82 Board

## Step 2: Connect Antenna

Connect the antenna to the AMB board, Figure 42. You may need a screwdriver or tweezers to push the clamp into place. This can take many tries and needs heavy pressure on the clasp to secure fully. Tug on the antenna to make sure it is properly in place.

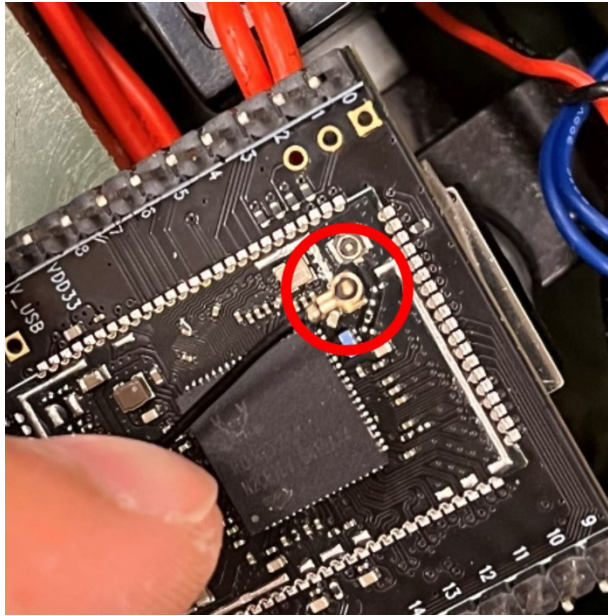


**Figure 42 Attach antenna to AMB 82 board**

## Step 3: Install AMB 82 Board in Wall Slot

Place the assembled AMB 82 boards in the wall slots, Figure 43. It is important to note the board with the AP program should be in the top of the turret (the upward facing camera). You can tell which is the AP board, by the labeled number. If the number is odd, it is the AP board and should be the upward facing camera. You might need to pull the camera through from the other side to move it into place. Again, the odd numbered board should be the upward facing camera and have the external antenna, the even numbered board should have the forward-facing camera. Antenna orientation will be discussed in detail later.



**Figure 43 Install AMB 82 board in wall slot**

Place the casing over the AMB and repeat the process with the wall-facing board (the even numbered board). The boards can come in and out of the slots for ease with wiring tests and connecting the antennas. Just make sure before final use they are secured in place.

#### **Step 4: Antenna Placement**

The antenna placement is important for the telemetry of the HIVE. The antenna connected to the forward-facing camera (even numbered board) can be stored inside the turret. Notice the antenna has an adhesive at the end. Remove the protective tape from the end of the antenna and secure the antenna anywhere inside of the turret. For the upward facing camera (odd numbered board) the antenna should be outside the turret. The antenna should run through the hole on the top of the turret adjacent to the camera hole. Run the antenna through the hole and connect the antenna to the board from the inside of the turret. Secure the antenna on the outside of the turret as shown in Figure 44. This antenna orientation will provide the best signal for video stream.



**Figure 44 Antenna placement on turret box**

The antenna should be facing backwards towards the back end of the tank.

#### **Step 5: Final Assembly**

After all wiring has been thoroughly tested, silicone sealant can be applied around the base of the turret, and super glue can be applied to the turret inner connector, Figure 45. Work through wiring section before fully securing turret.

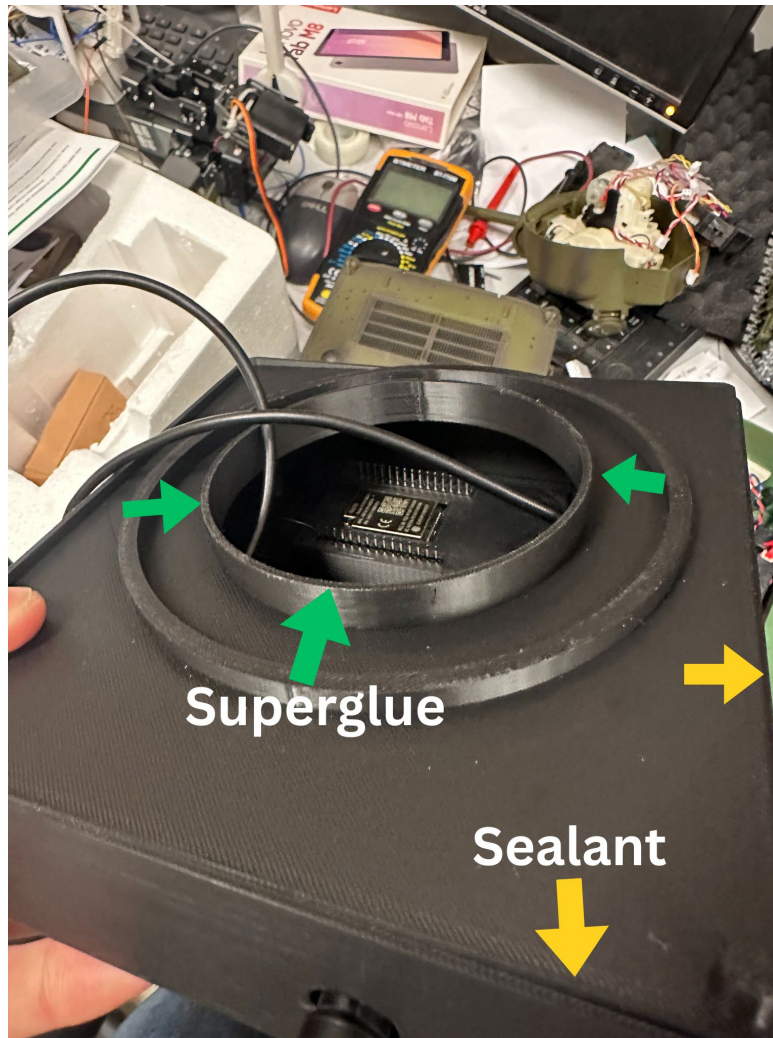


**Figure 45 Turret attachment with sealant and superglue**

The turret assembly is complete and can be added to the tank as in Figure 46. The turret can be added at any time but should only be fully secured after wiring is complete.



**Figure 46 Turret assembly mounted on tank**

## A.2 Tank Construction

Follow the instructions below to construct the tank. To avoid scratching table or workspace, place paper or other preventative layer between tank and work surface.

### Precursor

Before full tank construction, plug in tank battery as in Figure 47. You will need a charged battery to power tank after construction.



**Figure 47 Charging the tank battery**

### Step 1: Separate Tank Halves

Put the tank on its side and remove 4 screws to separate the top and bottom halves, Figure 48. Be sure to keep the screws to the side—you will need them again later in the process.

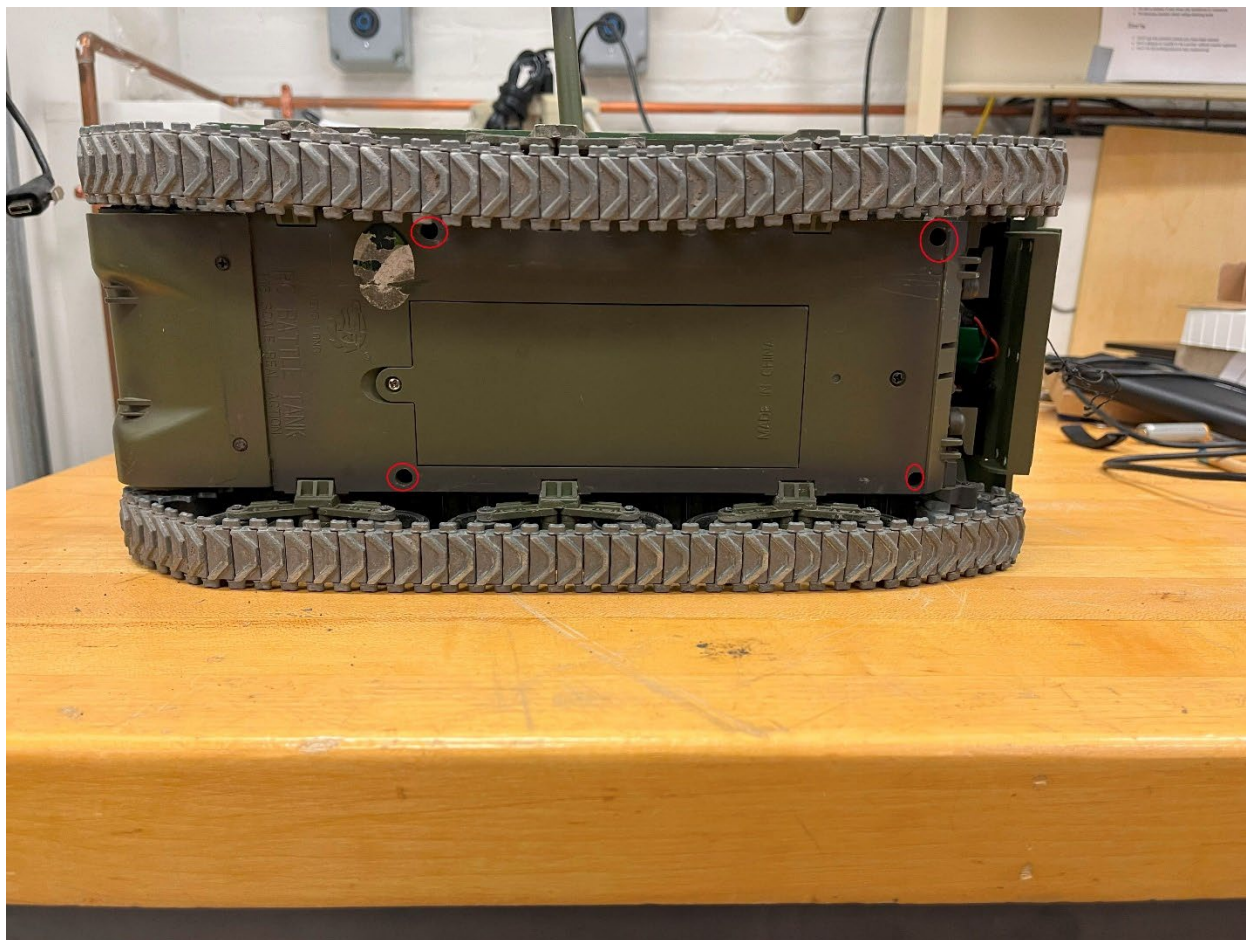


**Figure 48 Remove four screws from bottom of tank**

### **Step 2: Disconnect Wiring**

Remove all wiring connecting the bottom half of the tank from the top half. Figure 49 is what the top half of the tank should look like afterward.

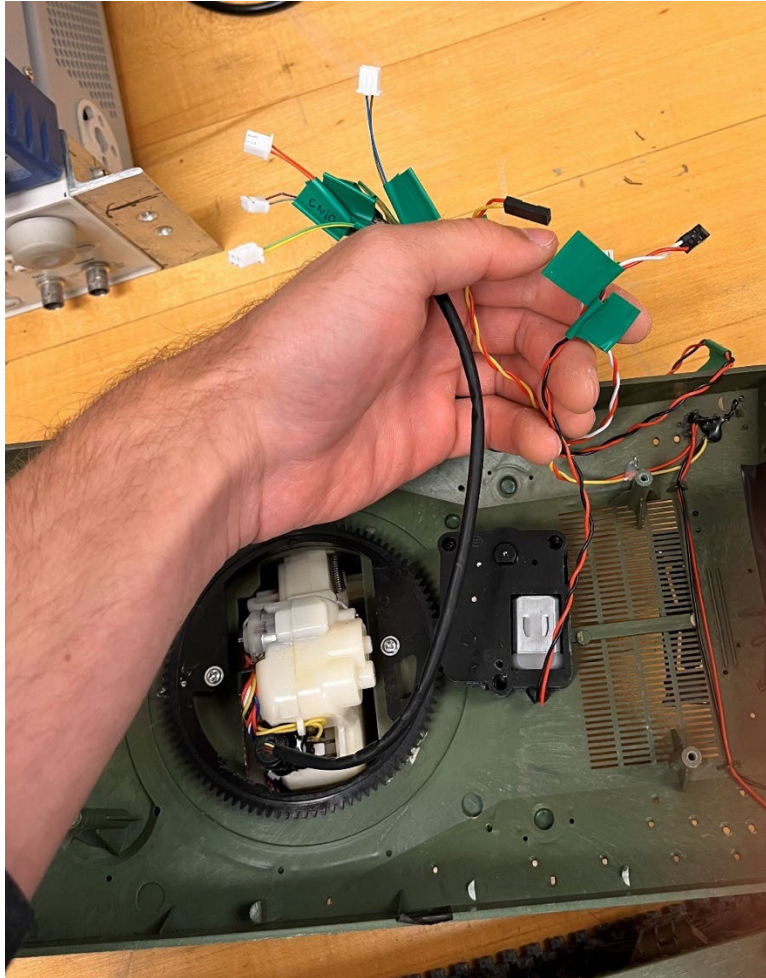


**Figure 49 Remove wires from bottom half of tank**

### **Step 3: Remove Speaker**

Return to the bottom half of the tank and find the speaker as in Figure 50. Remove it by unscrewing the two circled screws. The speaker should easily come off. If additional wiring is attached, you can remove it. The speaker and its wiring will not be used again.



**Figure 50 Remove two screws and speaker**

#### **Step 4: TK-7.0 Main Board**

The TK-7.0 main board should appear as shown in Figure 51, with the only connector left in place being the red wire indicated. The wires that were not connected to the top half of the tank but are not the circled red wire can be removed from the TK-7.0 main board and placed to the side somewhere in the tank. See the red/black and blue wiring positioned to the right side in this picture for reference.



**Figure 51 TK-7.0 board with one set of wires remaining**

#### **Step 6: Remove Turret Rotation Motor**

Remove the three screws shown in Figure 52 to remove the turret rotation motor. Pull firmly on the black box to remove the mechanism.

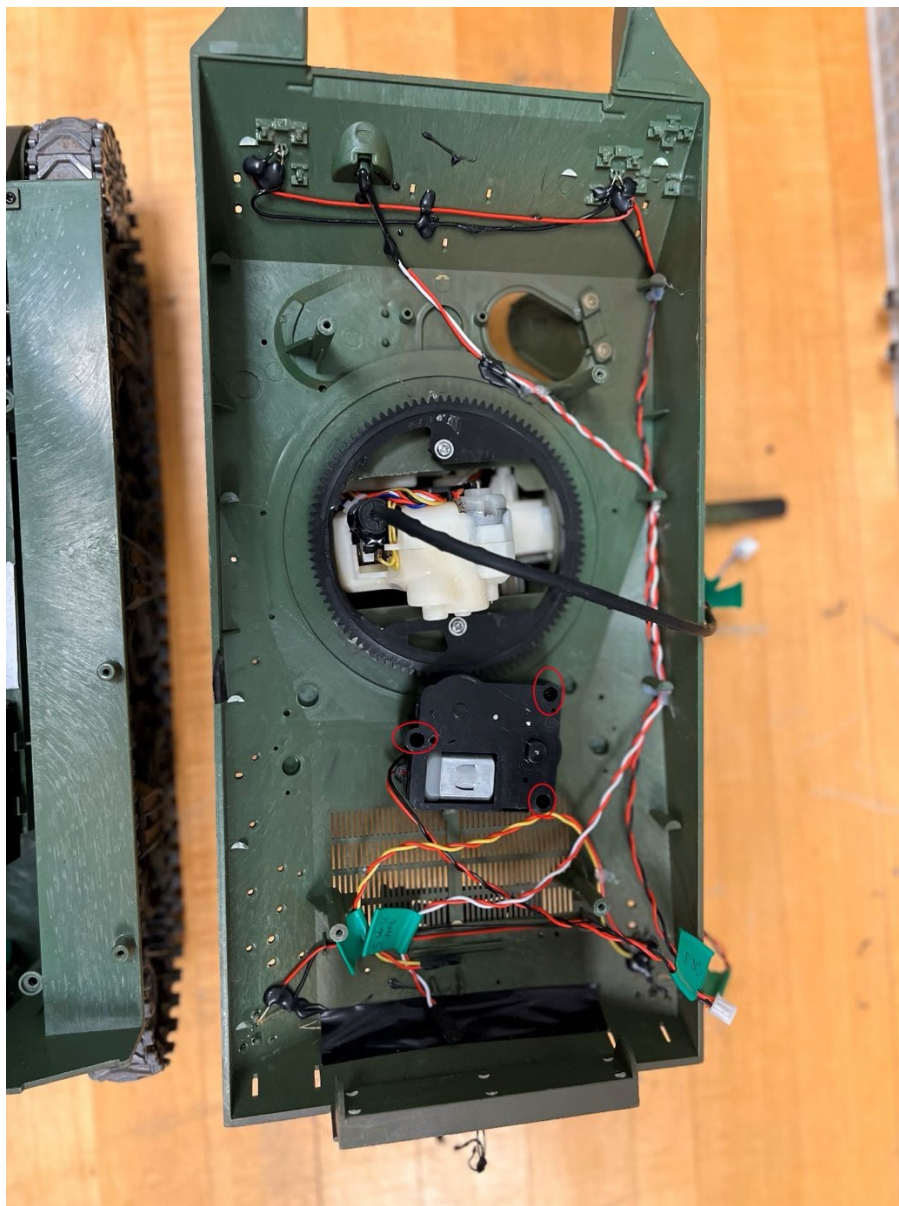


**Figure 52 Turret rotation motor with mounting screws indicated**

#### **Step 7: Separate Turret from Top Half**

With the turret rotation motor removed, remove the two silver screws indicated to separate the turret from the top half of the tank, Figure 53. The turret should fall off right away.

The tank should now be in three pieces with no wires connecting them.

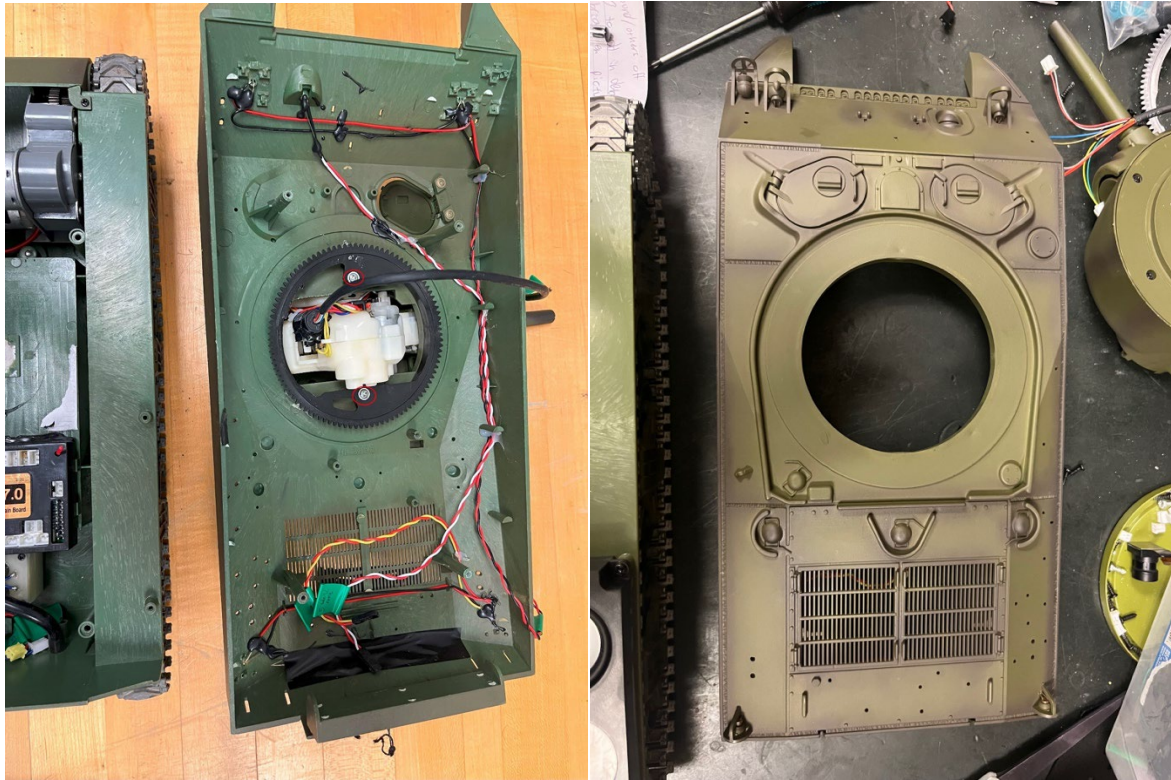


**Figure 53 Separation of turret from top half of tank**

#### **Step 8: Clean Up Top of Tank**

The top of the tank should look like Figure 54. All additional wiring on the top of the tank can be removed as pictured above. Some wiring may be difficult to remove or firm in place. Use wire cutters to help with the process.



**Figure 54 Bottom view of top of tank with wiring removed**

## **A.3 Wiring**

### **Safety Precautions**

While wiring tank make sure power is always off except for testing. Before testing make sure battery is charged and secured in place. If a wire is significantly fraying or damaged, do not use. Be extremely careful to connect positive and negative wires accordingly.

### **Step 1: Wiring from Main Board**

A 3-pin connector with two lines connected (roughly 22-20AWG) is needed to provide power to the AMB82 board. One set is provided in the kit for this purpose (Option #1) . For future construction, if needed, a similar assembly can be salvaged from the original turret. This process is described in Option #2.

### **Option #1**

Find in the kit the three-pin wire that is pictured in Figure 55.

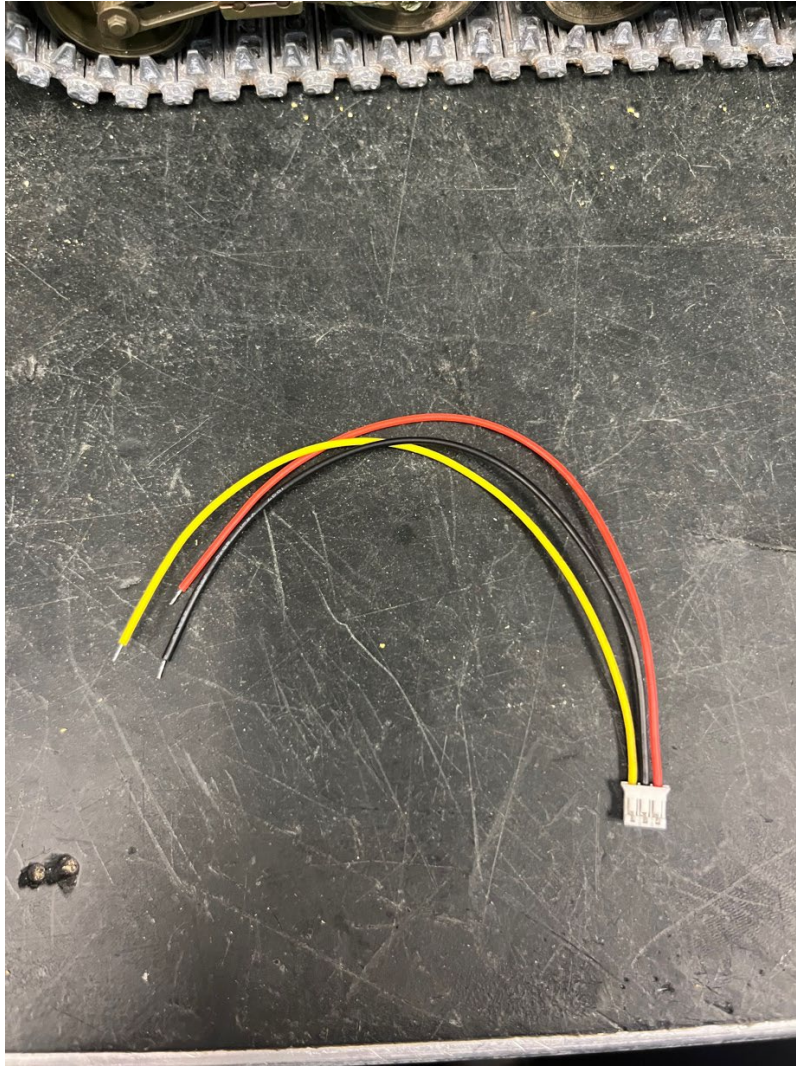


**Figure 55 Three pin wire**

The next step in this process is to cut off the red wire on the right-hand side. Strip the remaining wires to reveal about  $\frac{1}{4}$  in of wire, use wire strippers for this. Both changes appear in Figure 56.

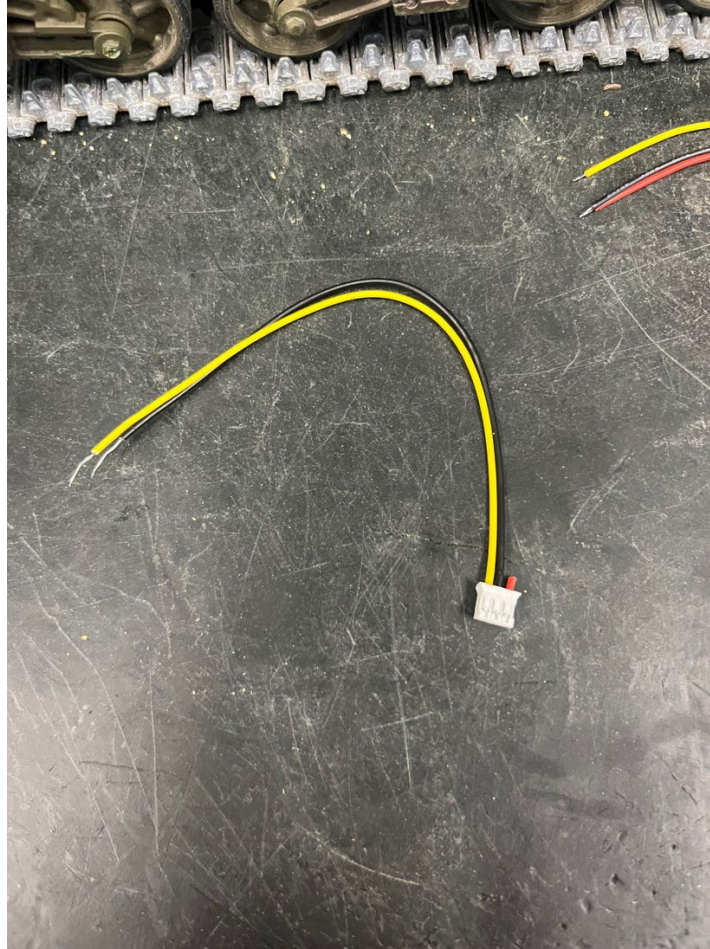


**Figure 56 Two pin wire set created from three pin wire set by trimming red wire**

The wire is ready for the connection in the next steps.

## Option #2

The next option requires harvesting wires from the previously removed turret.

Cut the zip tie holding the long wires together. These wires are connected to their own separate board (circled in Figure 57). Remove all wires from the board and locate the red, white and black wire pictured in Figure 58.

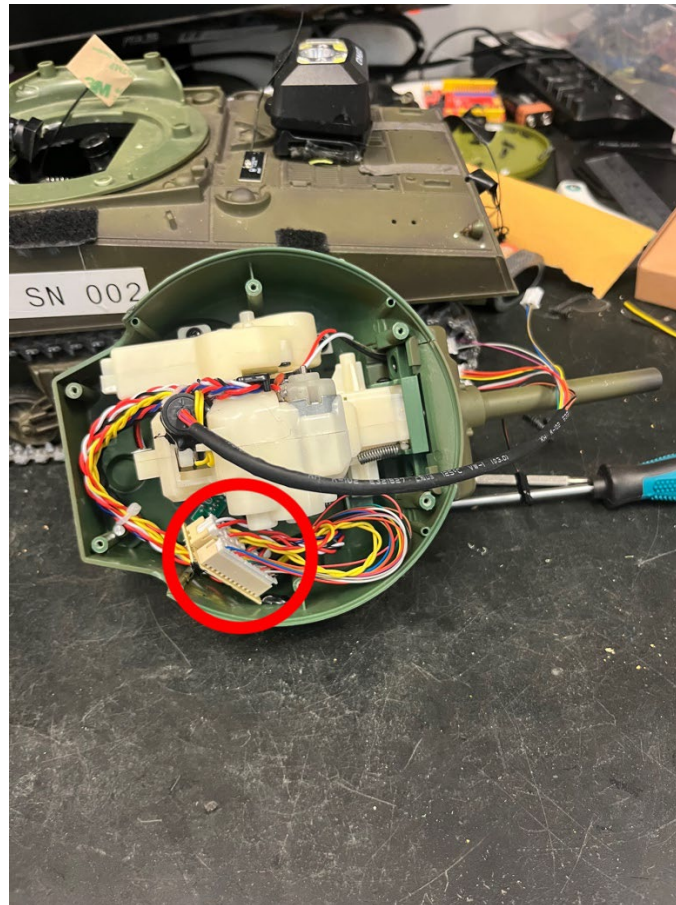


**Figure 57** Previously removed turret with zip tie indicated by red circle.

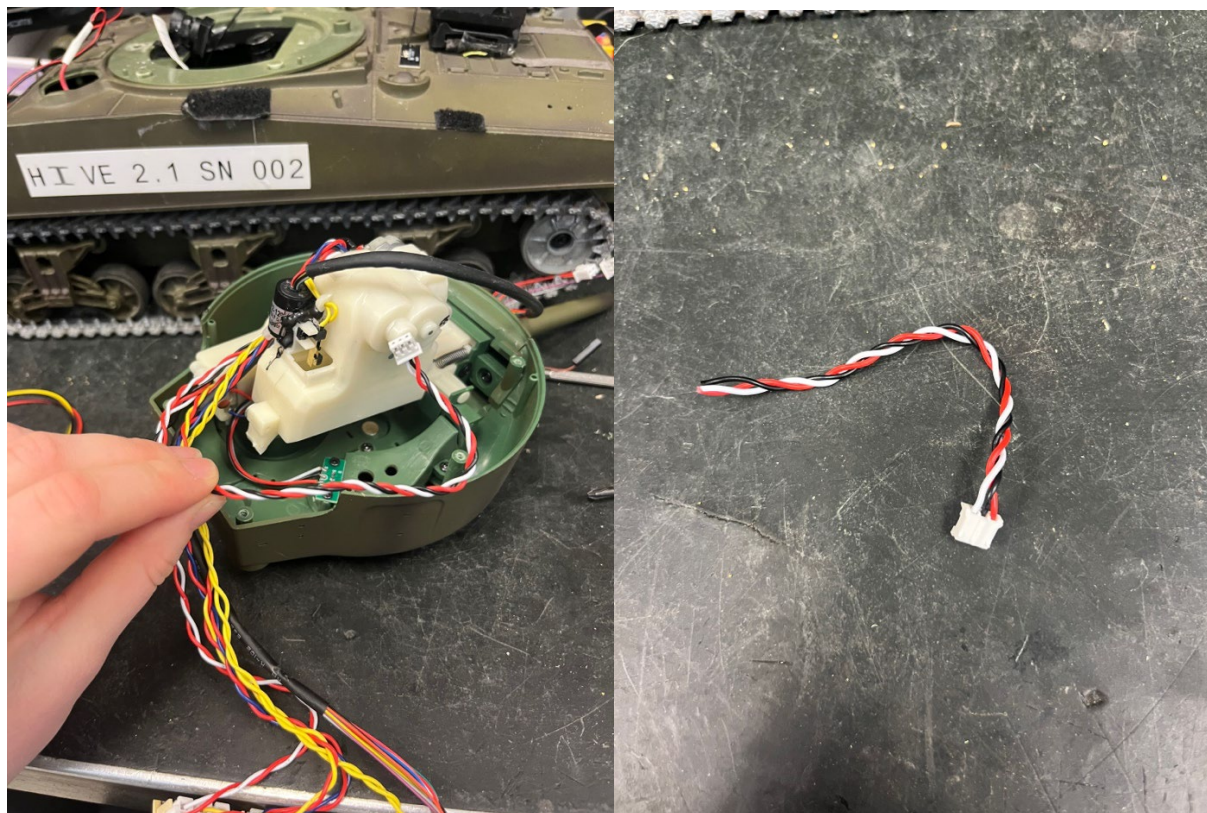


**Figure 58 Harvesting of three pin wire set from previously removed turret**

Cut the about 3 in from the white connector end. Untwirl the wiring and cut rightmost wire (the white). The remaining two wires should be stripped back to reveal about  $\frac{1}{4}$  in of wire. This is pictured in Figure 59.

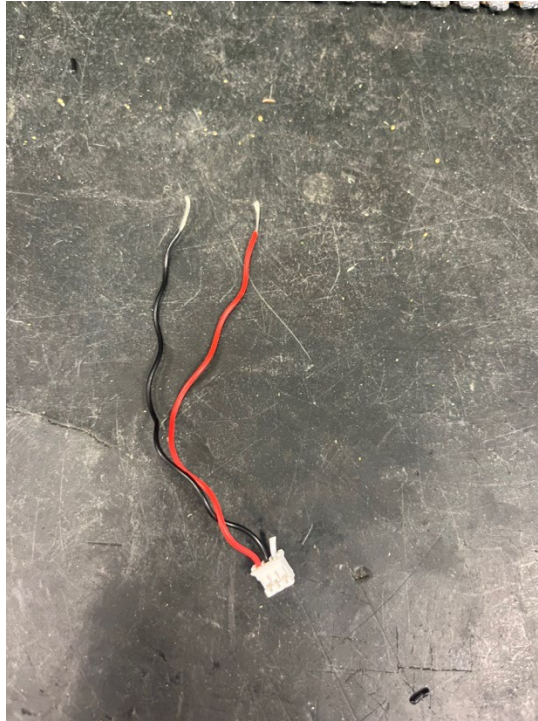


**Figure 59 Two pin wire set harvested from previously removed turret**

The wiring is now complete and ready for connection in the following steps.

**Step 2: Connect to Wire Terminal`**

Locate the 4-to-2 lever terminal as in Figure 60. The wire described in the previous step will be connected to the two-hole side of this terminal, the side pictured below.

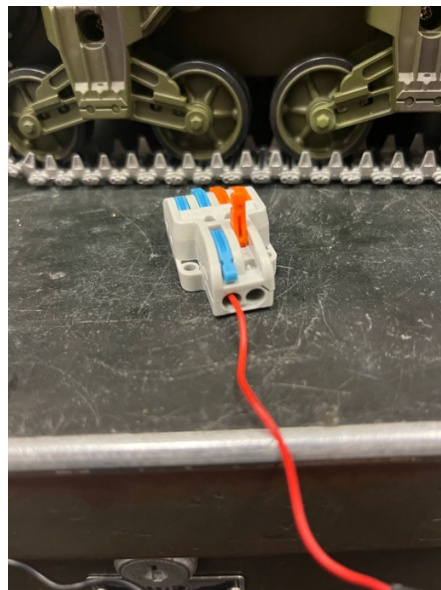


**Figure 60 4 to 2 lever terminal**

To open the ports, the blue and orange clips should be snapped up, as shown in the example above. Slide the exposed wire into the hole while the clips are open. Once the wiring is in the hole, snap the clip down to secure the wire. Check to see if the wiring is properly inserted by tugging on the wire—the wire should stay in place. When both wires are secured, it should look like Figure 61.

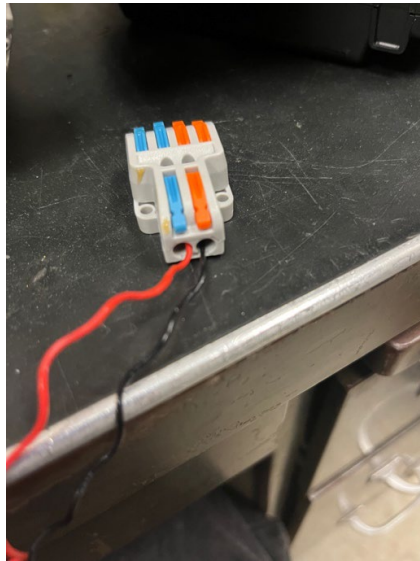


**Figure 61 4 to 2 lever terminal with wires attached**

### **Step 3: Connect to TK-7.0 Main Board**

For this connection, use the port that is circled in red in Figure 62. Do not use any other ports. You may burn the AMB82 board since it only takes 3.3V, and some of the ports on the TK-7.0 board output 6V. You will only be connecting to the two leftmost pins. Of the two leftmost pins, the one in the middle is the negative pin, and the leftmost one closest to the wall is the positive pin. Double check to ensure the correct pins are located.



**Figure 62 TK-7.0 board with 3.3V port circled**

Connect the white plug to the port, make sure the wire on the leftmost side (the positive pin) is lined up with the leftmost pin, and the black wire is lined up with the middle pin (the negative pin), as in Figure 63. This is pictured below. The wires do not always connect with the pins easily—you may have to maneuver the wiring slightly for the pins to fully connect. Colors may change if using differing wires. The most important thing is to keep track of the positive and negative charges.

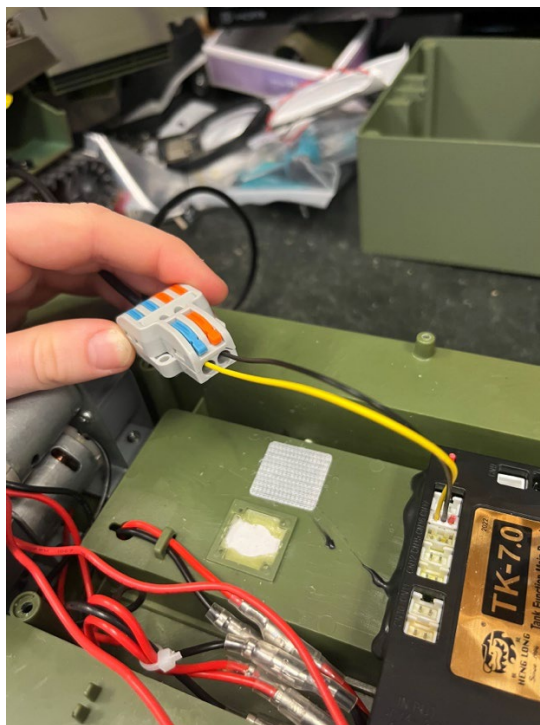


**Figure 63 4 to 2 terminal connected with two wires to TK-7.0 board**

#### **Step 4: Black Connection Cables**

You will need two black connection cables with pigtail wires, locate them in your kit provided. These wires connect the AMB boards to the 4-to-2 terminal. When connecting the cables to the AMB Boards, you will need a right-angle connector, also provided. You will only need this connector for the upward-facing camera board (odd numbered). It is very important when connecting the cables to AMB boards you use only the left-side USB connector for both boards. This means the left most port off the board while the camera is facing upwards.

You may need to strip the wiring on the pigtail side of the cables. Use the wire stripper to lengthen the amount of exposed wire.

An example of a stripped back cable is shown in Figure 64. Repeat on the other cable.



**Figure 64 Two wire black connection cable with stripped end**

**Step 5: Connect Cables with TK 7.0 Mainboard**

Connect the wiring from the cables the same way you connected the wires in Step 2. Make sure that the red wiring on each cable, the positive, is connected to the positive side, blue side in the example above, and the black wiring, negative, is connected to the negative side, orange in this example, as in Figure 65.

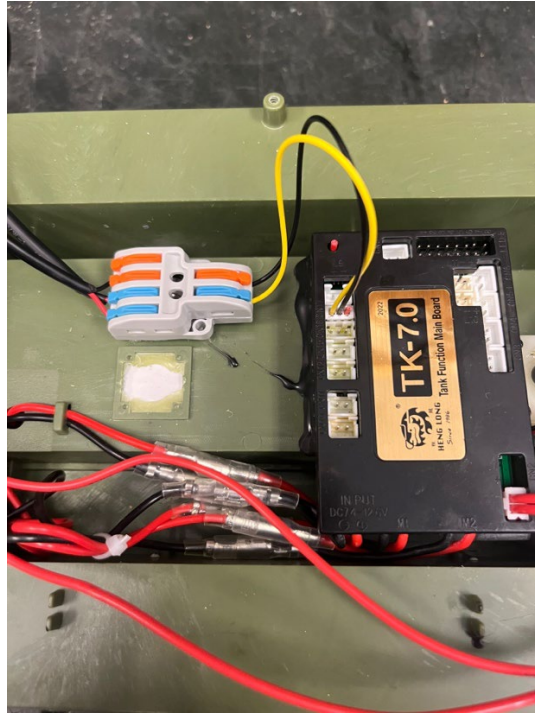


**Figure 65 Two two wire black connection cables connected to 4 to 2 terminal block**

Flip the tank's switch (located near the main motor, opposite the TK70 Board) to the ON position.

When wiring is complete the AMB82 boards should light up red showing a steady connection. If red light is wavering this is a sign of a weak power connection. Check wiring and ensure all connections are secure.

#### **Construction Refinement**

Secure the 4-to-2 terminal to the tank as pictured in step five with Velcro, strong double-sided tape, or another adhesive.

Secure headlamp to top of turret with Velcro or another adhesive as in Figure 66. The exact position of the light is up to the user. The Velcro allows for adjustment if different lighting positions prove better than others. Make sure light is charged before use inside culverts.



**Figure 66 Headlamp attached to turret**

The reel system uses a carabiner to attach the reel system to the HIVE. This carabiner attaches to the top half of the tank through a zip tie. Slip and secure the zip tie through the back of the top half of the tank as in Figure 67.



**Figure 67 Ziptie attachment to tank top for carabiner**

At this point, wiring should be finished and functional. The turret should be assembled and attached with the cameras, boards, and antennas secured. For testing and initial use, the turret does not need to be secured fully with sealant.

Return the first four screws removed at the bottom of the tank to secure the top and bottom halves of the tank together before use.

## **A.4 Video Feed**

### **Step 1: Install VLC Media Player**

To access the video feed from the HIVE 2.1, install VLC media player. Look up VLC Install. Download. If VLC media player is unable to be downloaded on professional devices search for an acceptable media player. Other software's should be able to stream if you can connect a network.

### **Step 2: Connect to Tank Wi-Fi Network**

Once the battery and VLC are installed and the tank is powered on, you should be able to see "Tank\_Vision" as a new Wi-Fi network option, Figure 68. Connect to that network.

Note that the Wi-Fi network is named Tank Vision. When you power on the tank a version of the Tank Vision Wi-fi should appear as a network option. The title is adjusted according to the numbers on the AMB

boards. For example, if the boards are labeled 23 and 24, the Wi-Fi network would be called Tank\_Vision\_23/24.

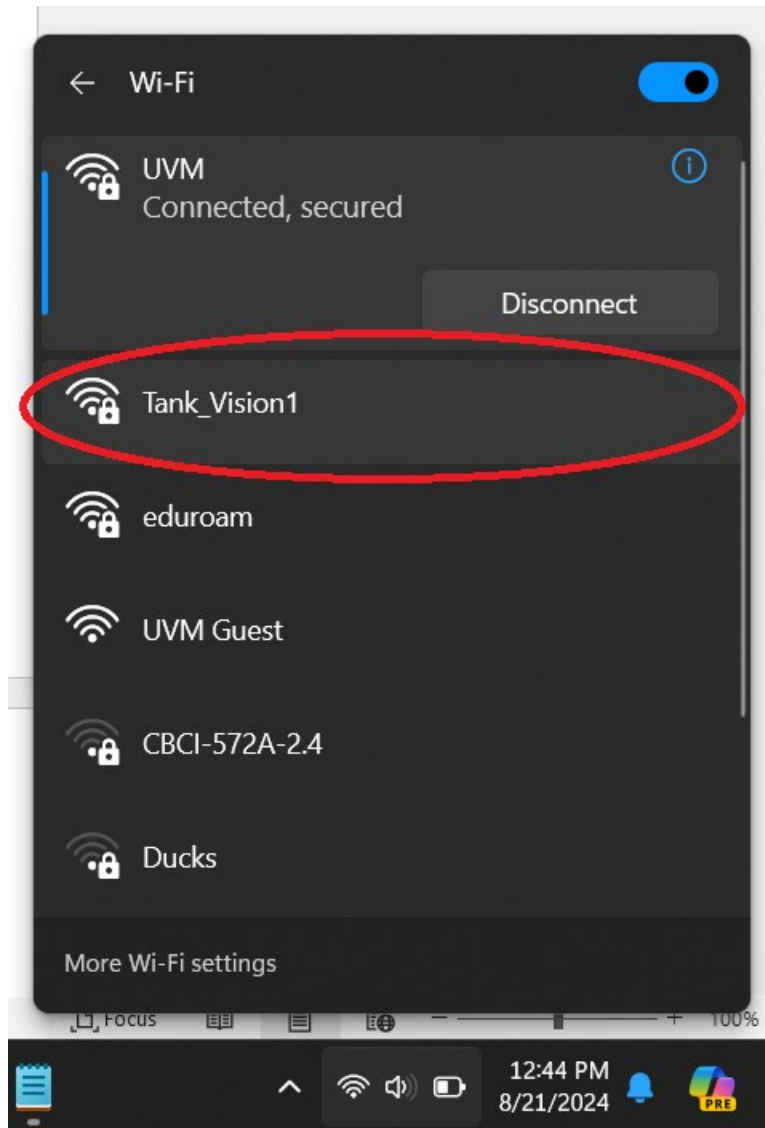


**Figure 68 WiFi menu view with Tank Vision link**

The password for the Wi-Fi is "appassword".

### **Step 3: Open Network Stream in VLC**

Open VLC media player and click the "Media" dropdown, then click "Open Network Stream," Figure 69.

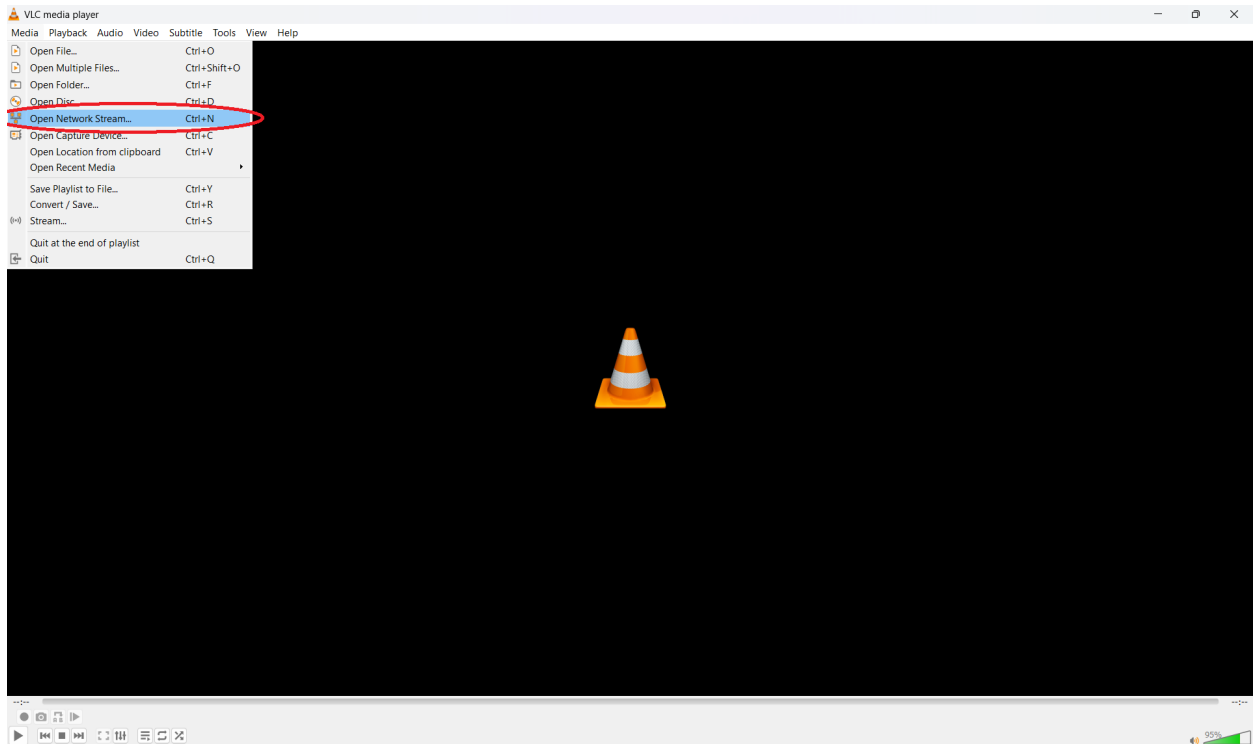


**Figure 69 VLC media player menu with Open Network Stream tab**

In the Network stream tab called "Open Media," enter the IP address:

rtsp://192.168.1.1:554

This accesses the stream from the AP AMB.

To get the stream from the other AMB at the same time, simply open another VLC window and use the IP address:

rtsp://192.168.1.100:554

or

rtsp://192.168.1.101:554

(if the first IP does not work)

**Step 4: Adjust Caching Settings**

Before hitting Play, click the "Show more options" dropdown, Figure 70.

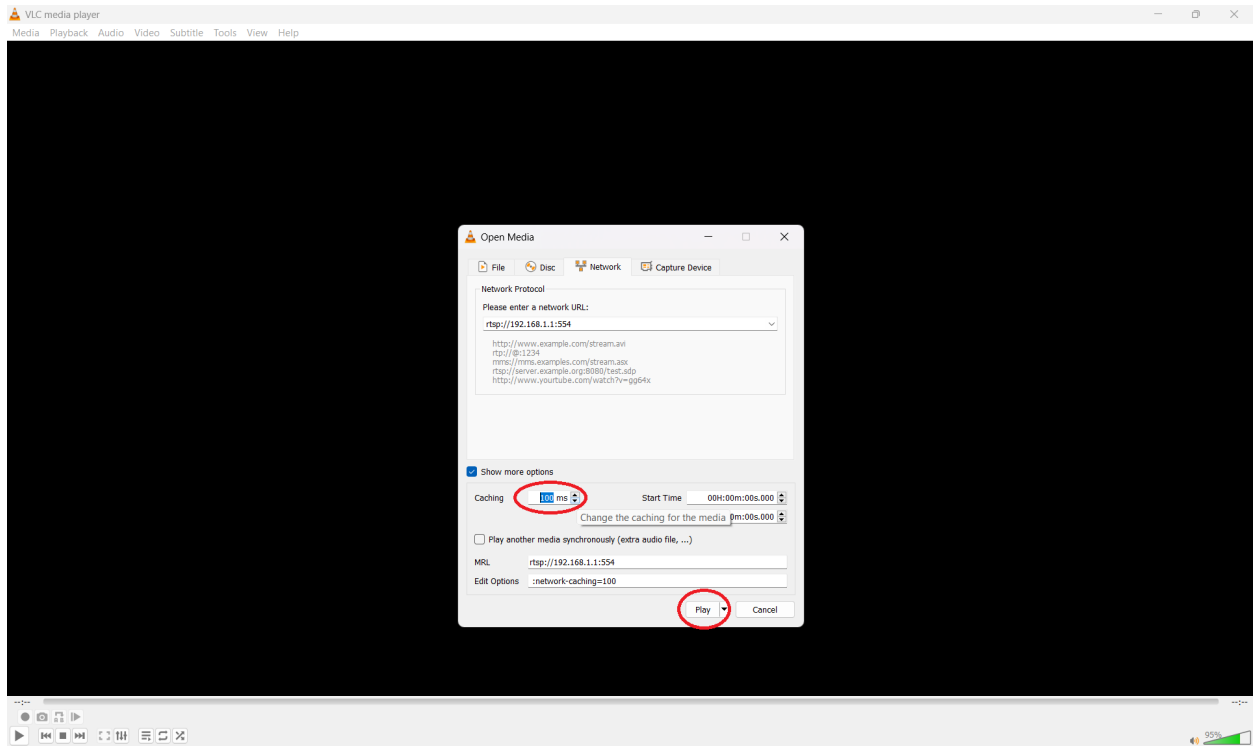


**Figure 70 Menu with Caching settings**

In the options below, change the "Caching" from 1000ms to 100ms. If this step is missed, there will be a very large delay on the video feed.

Hit Play and the video will start. Run the two VLC monitors next to each other to get simultaneous views.

### **Step 5: Optional - Use TP-Link AC600 High Gain Antenna**

This step may be unable to be achieved on professional devices. If so ignore and continue the instructions.

A final improvement to signal quality is to use the TP-Link AC600 High Gain wireless antenna. This should be easy to use—simply plug it into an available USB port and install the drivers with the link below:

<https://www.tp-link.com/us/support/download/archer-t2u-plus/>

To ensure that the TP-Link is being used, disable any internal Wi-Fi card by going to Network & Internet > Advanced Network Settings and disabling any internal Wi-Fi so the only network adapter enabled is the TP-Link, Figure 71.

## Network & internet > Advanced network settings

### Network adapters

|                                                                                                                                                                   |                  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
|  <b>Wi-Fi</b><br>UVM   Intel(R) Wi-Fi 6E AX211 160MHz                            | <b>Disable</b> ▾ |
|  <b>Ethernet</b><br>ExpressVPN TAP Adapter                                       | <b>Enable</b> ▾  |
|  <b>Bluetooth Network Connection</b><br>Bluetooth Device (Personal Area Network) | <b>Disable</b> ▾ |

### More settings

|                                                                                   |   |
|-----------------------------------------------------------------------------------|---|
| <b>Advanced sharing settings</b><br>Change network discovery and sharing settings | > |
| <b>Data usage</b>                                                                 | > |
| <b>Hardware and connection properties</b>                                         | > |
| <b>Network reset</b><br>Reset all network adapters to factory settings            | > |

### Related settings

|                         |                                                                                       |
|-------------------------|---------------------------------------------------------------------------------------|
| <b>Windows Firewall</b> |  |
| <b>Internet options</b> |  |

**Figure 71 Network setup menu with internal Wi-Fi card disabled**

## A.5 Reel System

### Video Instructions:

<https://www.youtube.com/watch?v=P9ETRvzngZI>

Instructions for assembling the reel system appear in Figure 72 to Figure 84.



Figure 72 Takeup reel with parts needed for assembly

#### TOOLS AND SUPPLIES NEEDED:

- ☐ Phillips head screwdriver
- ☐ Super glue
  - o <https://a.co/d/1o3ISP6>



Figure 73 Tools and supplies needed for assembly

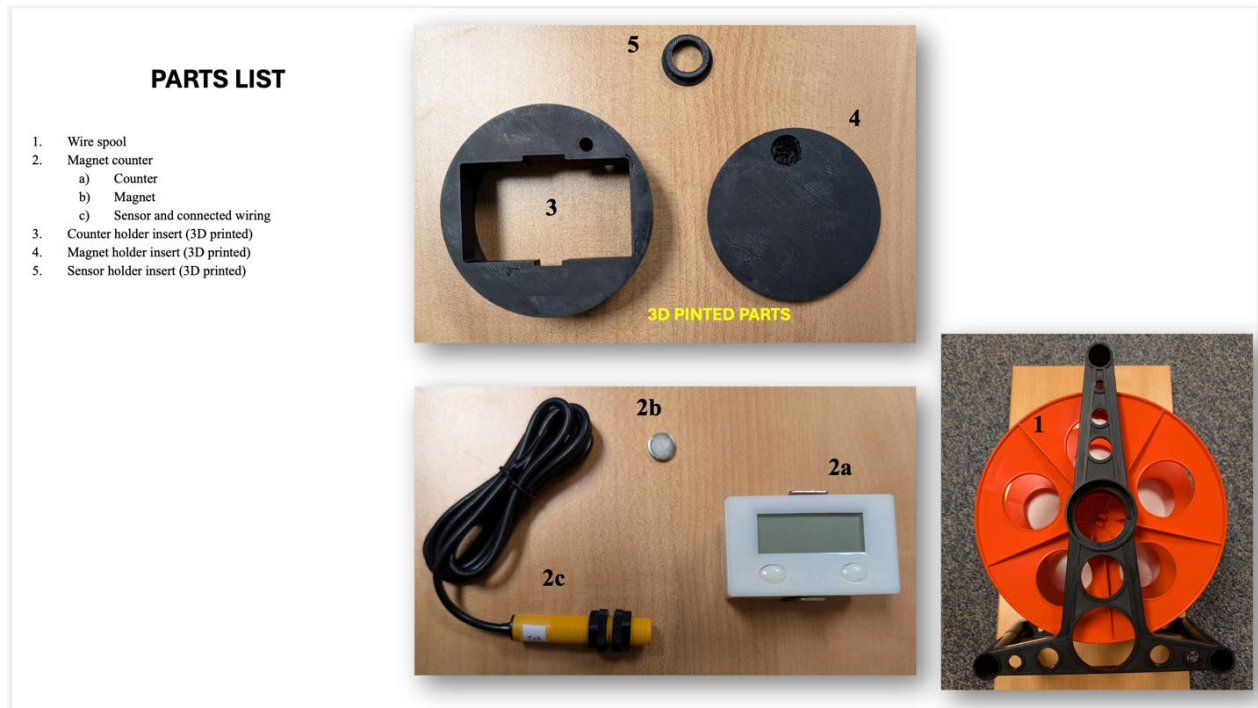


**Figure 74 Parts needed for reel assembly**

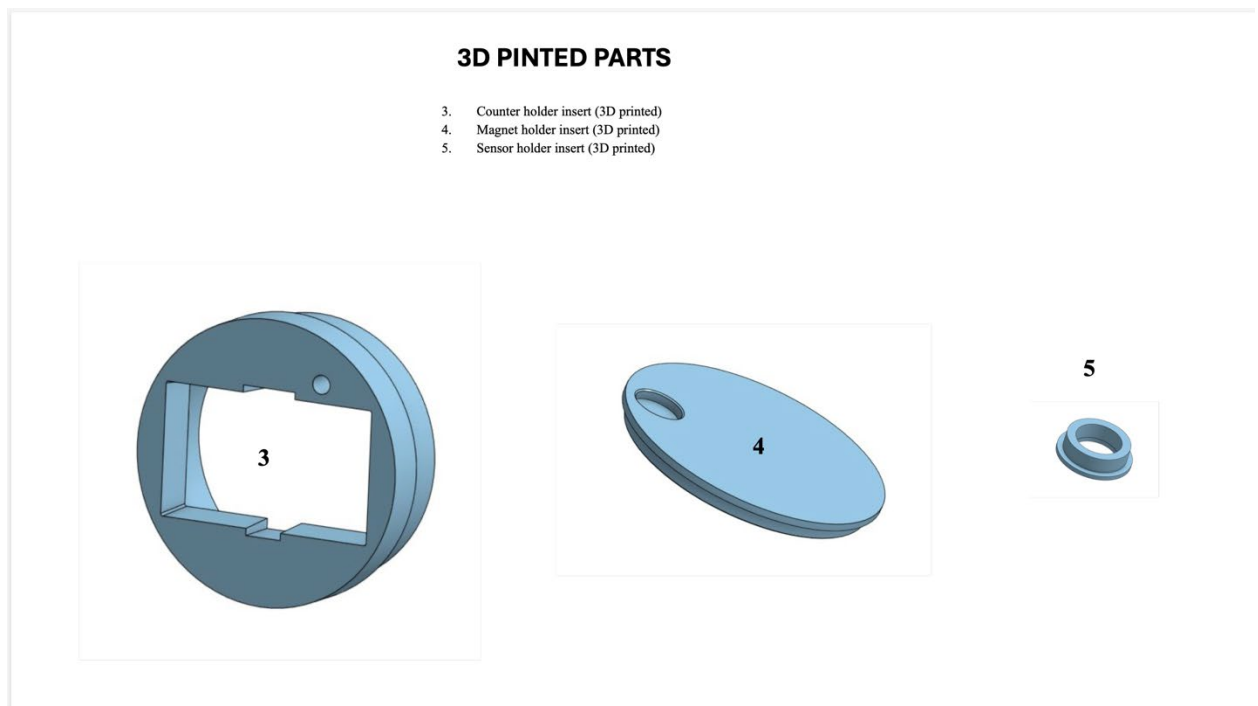
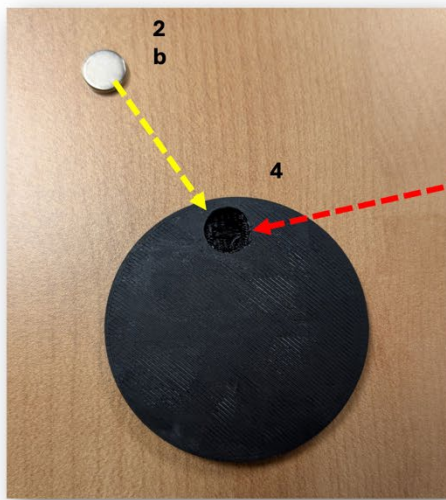


**Figure 75 3D printed parts required for reel assembly**

### STEP 1

Insert the magnet (*Part 2b*) into the magnet holder insert - 3D printed (*Part 4*)



*Use super glue to make sure it is permanently secured in place. Place a small amount of superglue in the hole on the 3D printed part.*

*Then press fit the magnet in the hole.*



**Figure 76 Insertion of magnet into magnet holder for reel rotation counter**

### STEP 2

Insert the counter (*Part 2a*) into the counter holder insert - 3D printed (*Part 3*)

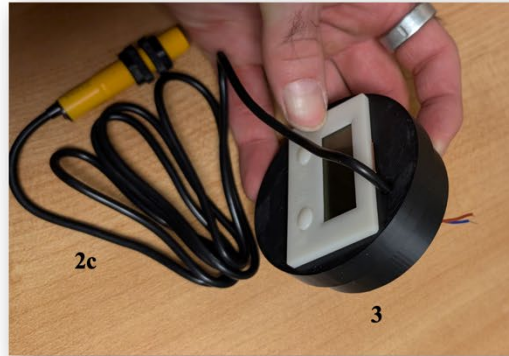
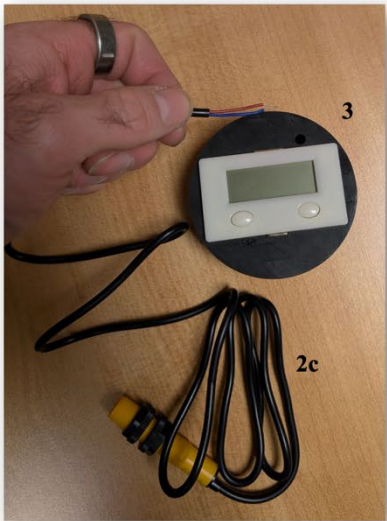


Press it all the way in



**Figure 77 Insertion of counter into counter holder**

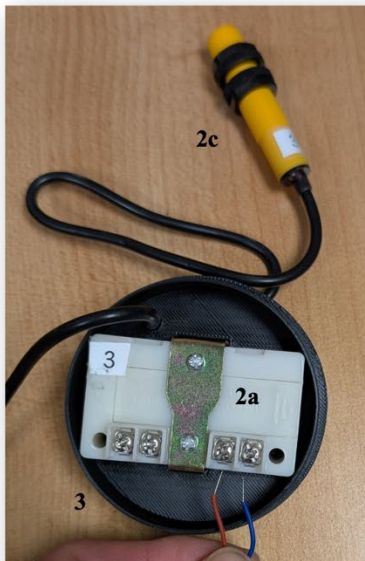
**STEP 3** Feed the wire from the sensor (*Part 2c*) through the hole in the counter holder insert - 3D printed (*Part 3*)



Pull all but 7" of the wire through the hole

**Figure 78** Feed wire from magnetic sensor into hole in counter holder insert

**STEP 4** Attach the wires from the sensor (*Part 2c*) to the screw terminals on the back of the counter (*Part 2a*) using a Phillips head screwdriver.



- Use the screw terminal on the right side
- Labeled "Count"
- Blue wire to the negative terminal
- Red wire to the positive terminal

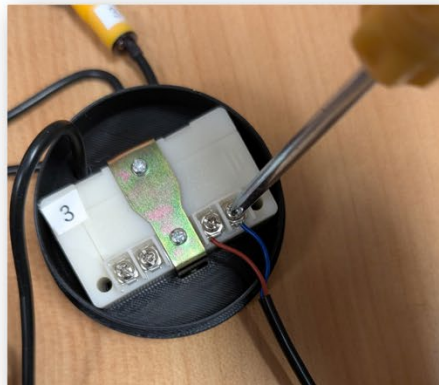


**Figure 79** Attach sensor wires into screw terminals on back of counter

- STEP 5** Remove the top nut from the sensor (*Part 2c*) and insert it into the Sensor holder insert -3D printed (*Part 5*)

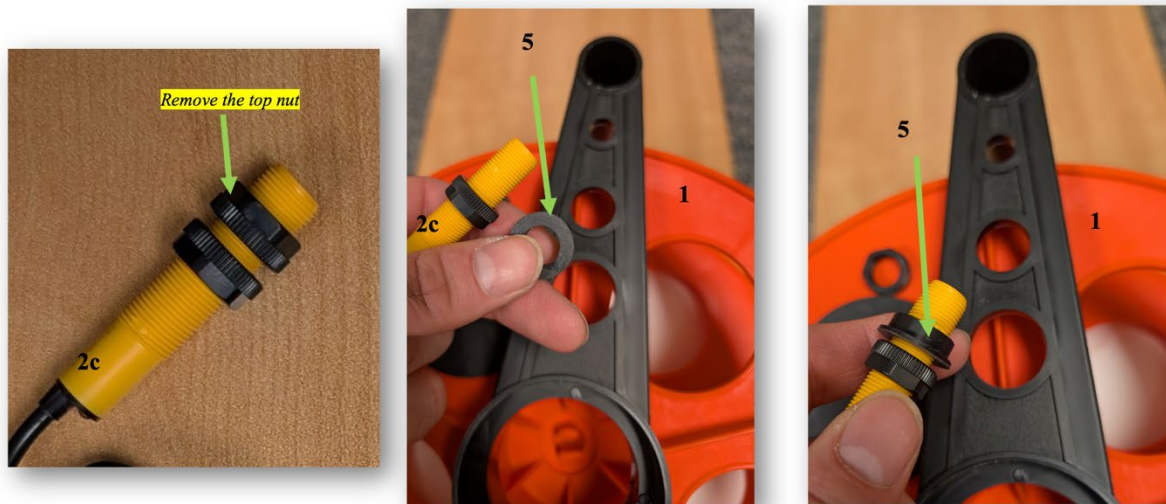


**Figure 80 Attachment of sensor to reel**

- STEP 6** Insert the sensor(*Part 2c*) and Sensor holder insert -3D printed (*Part 5*) into the second hole on the wire spool (*Part 1*)

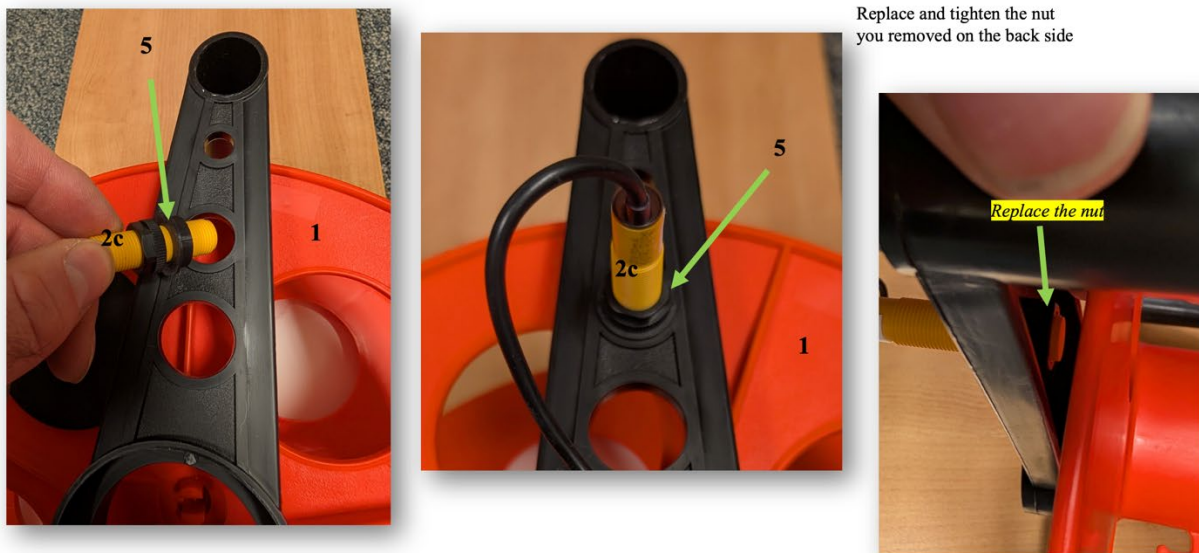


**Figure 81 Insertion of magnet sensor into reel**

**STEP 7** Coil the extra wire from the sensor (*Part 2c*) and use place it in the cavity in the center of the wire spool (*Part 1*) Then press fit the counter holder insert (*Part 3*) into the hole in the center of the spool (*Part 1*)



**Figure 82 Coil wire and insert counter into reel**

**STEP 8** Press fit the magnet holder insert - 3D printed (*Part 4*) into one of the holes on the side of the wire spool (*Part 1*)

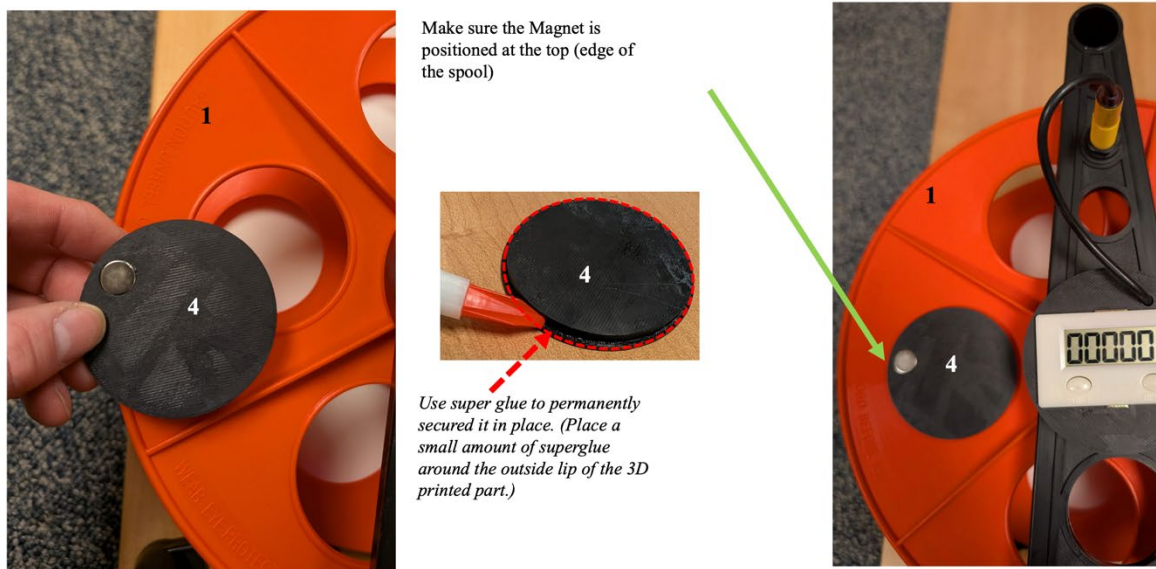


**Figure 83 Press the magnet and magnet holder into side of wire spool**

## A.6 Waterproofing

### Safety Precautions

The use of these chemicals is dangerous and should be done with taking all the following safety precautions in place. Before the use of either spray, make sure you are in a well-ventilated area ex. outside, under a fume hood. Make sure to be wearing facial protection like a ventilator or heavy face mask to avoid inhalation of chemicals. Always wear safety glasses or goggles while handling spray. Use gloves when spraying or handling the tank post waterproofing while sprayed wires are exposed. Make sure to lay a tarp or preventative layer down under the tank to avoid damage to work surface.

### Step 1: Polyurethane Spray



**Figure 84 Can of polyurethane waterproofing spray**

The polyurethane spray is pictured in Figure 84. Coat the inside of the tank making sure all wiring is completely covered. You can do this by only separating the tank in half as shown in the first step of the Tank Construction section. AMB boards should be fully sprayed to avoid water damage. Tape over the camera lenses while spraying to avoid damage. You will have to remove the casing from the upward facing camera to expose all electronics. Wait about three or four hours for spray to completely set.

## Step 2: Corrosion X



Figure 85 Can of CorrosionX waterproofing spray

Take the same precautions and apply this spray in the same way as the Polyurethane spray, Figure 85. This coat will take a few days to set and may not ever fully dry. With this in mind, handle the tank with caution to avoid getting chemicals on skin or in eyes. Use gloves when reassembling the tank.

### Program AMB 82 Boards

There are two AMB-82 boards on the HIVE 2.1, and each requires a different program to be uploaded for the tank to function properly.

The uploading of this code requires certain software, if your professional device cannot download Arduino IDE, this process will not work.

### **Step 1: Install Arduino IDE**

Install the latest version of Arduino IDE. You can download Arduino from any standard web browser by searching "Arduino download" and navigating to the official Arduino Software page, Figure 86.

## Bring Your Projects to Life with Arduino Software

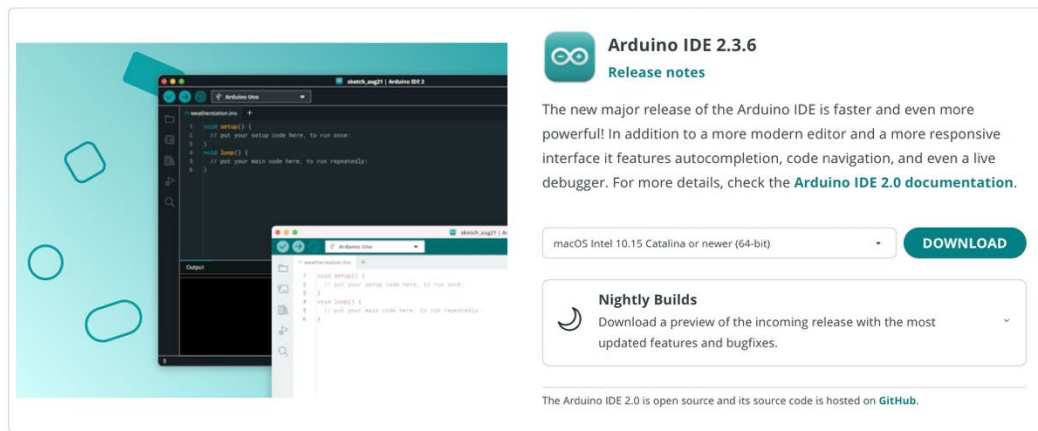


**Figure 86 Website showing Arduino IDE**

The website should display a page similar to the one shown above. Click download and open the installer from your downloads when finished.

Note: If working on Microsoft Windows, you may need to switch out of S mode because Arduino IDE is separate from the Microsoft Store.

### **Step 2: Configure Arduino Preferences**

Once installation is finished, go to Preferences, Figure 87.

Note: If working on a Mac or device other than a Microsoft computer, Arduino might not have the preferences page in the same location. If so, try pressing Command and Comma at the same time and a preferences page should appear. If this still doesn't work, search for how to reach the Arduino preferences page on your specific device.

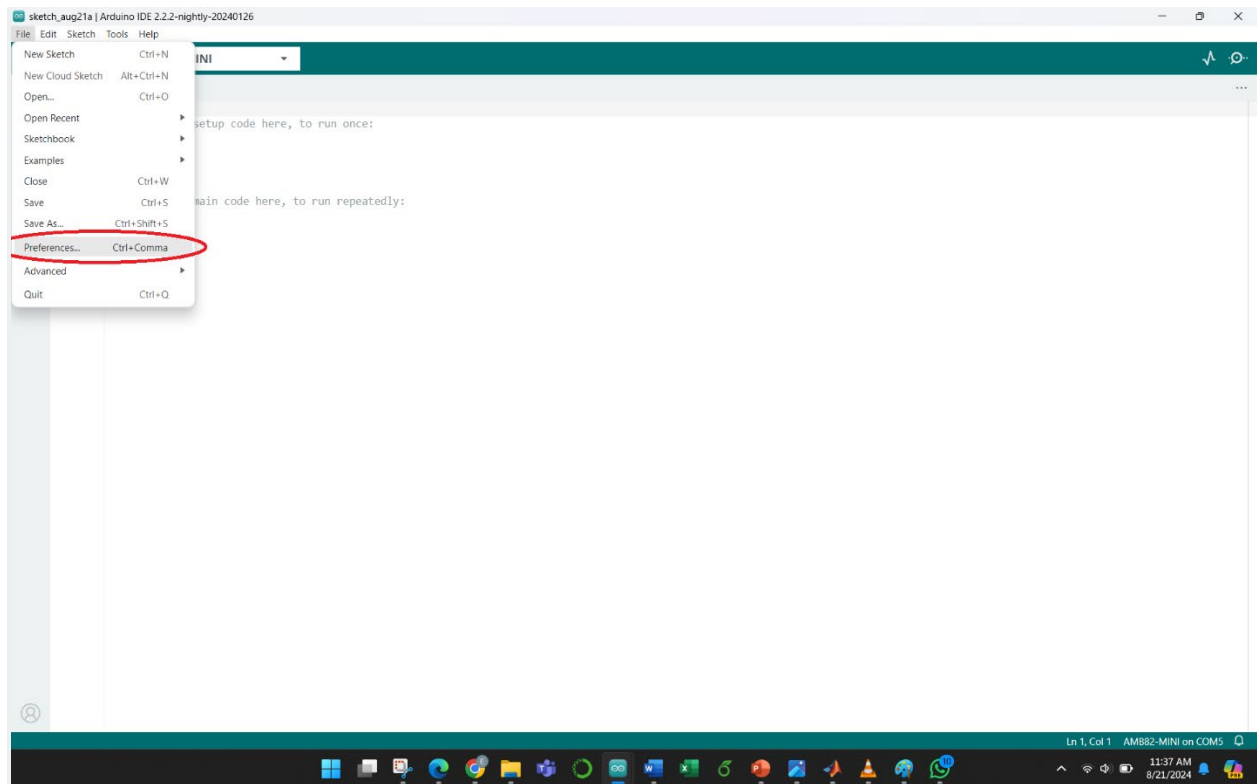


**Figure 87 Website showing how to configure Arduino preferences**

Inside the Preferences tab, locate the text box next to "Additional boards manager URLs" and paste the following URL:

Configure Arduino Preferences

Click OK, Figure 88.

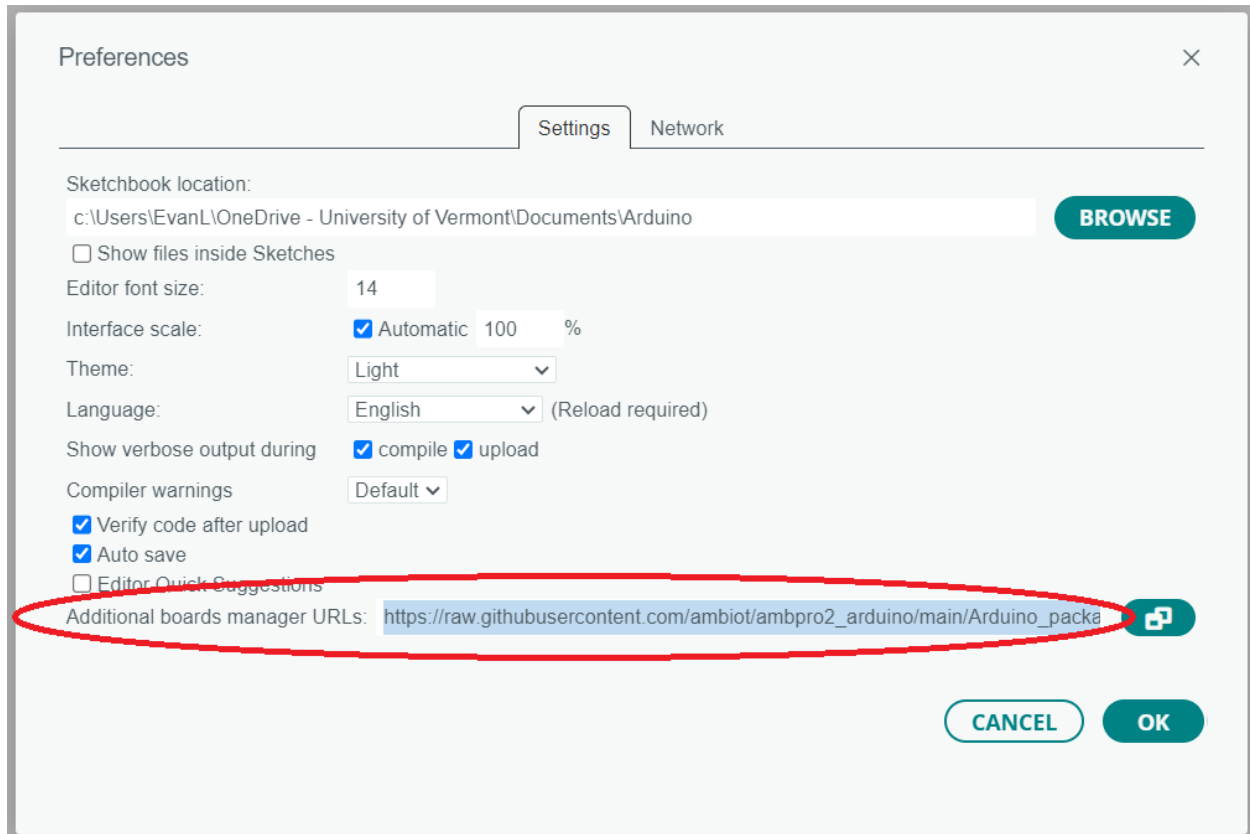


**Figure 88** Arduino preferences tab with github link

### **Step 3: Install FreeRTOS Library**

Next, install the FreeRTOS library by Richard Barry.

To install the library, click the Library Manager icon on the side of your tab (the book icon), Figure 89.

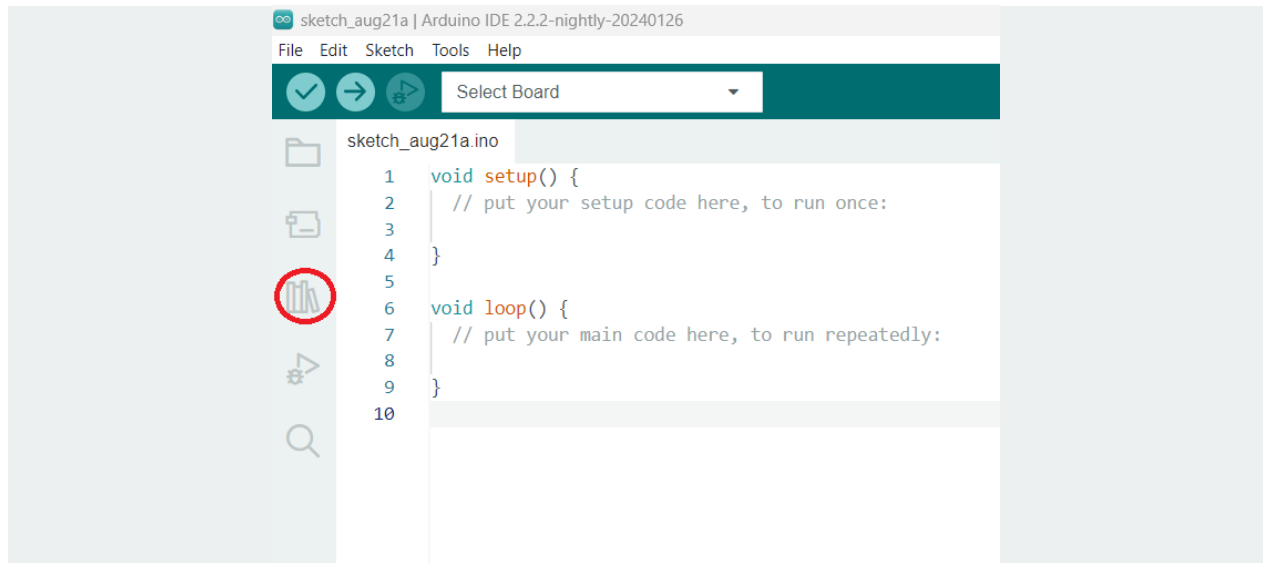


**Figure 89 FreeRTOS Library**

Search for "FreeRTOS" and install, Figure 90.

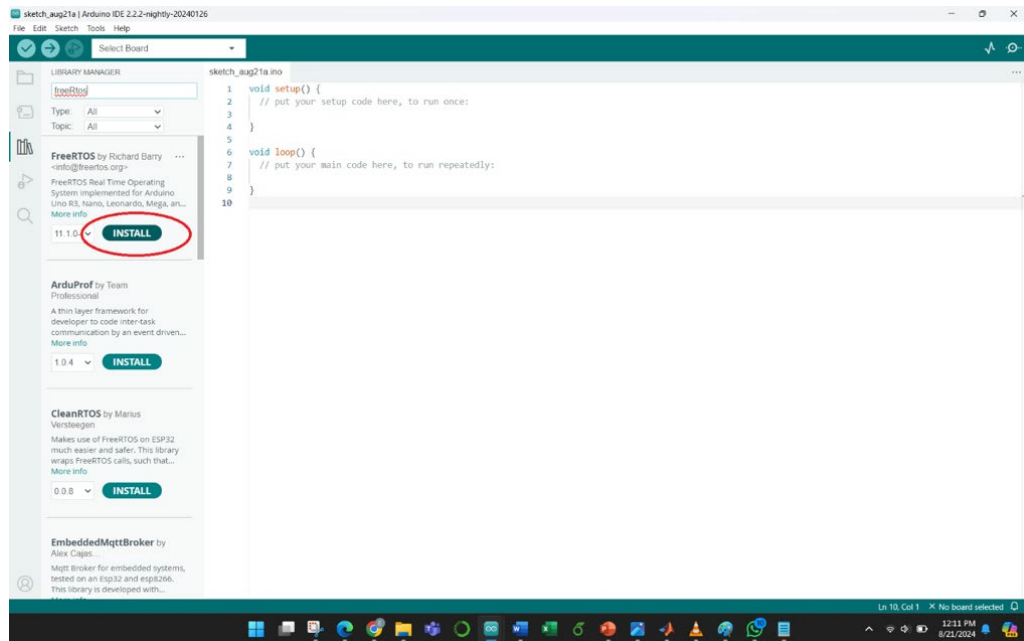


**Figure 90 Install tab on FreeRTOS library**

#### Step 4: Connect the AMB Board

Plug the AMB into your computer. It should have a red indicator light when plugged in properly, Figure 91. Use the right-hand mini-USB port as shown below. The left-hand port does not upload code.

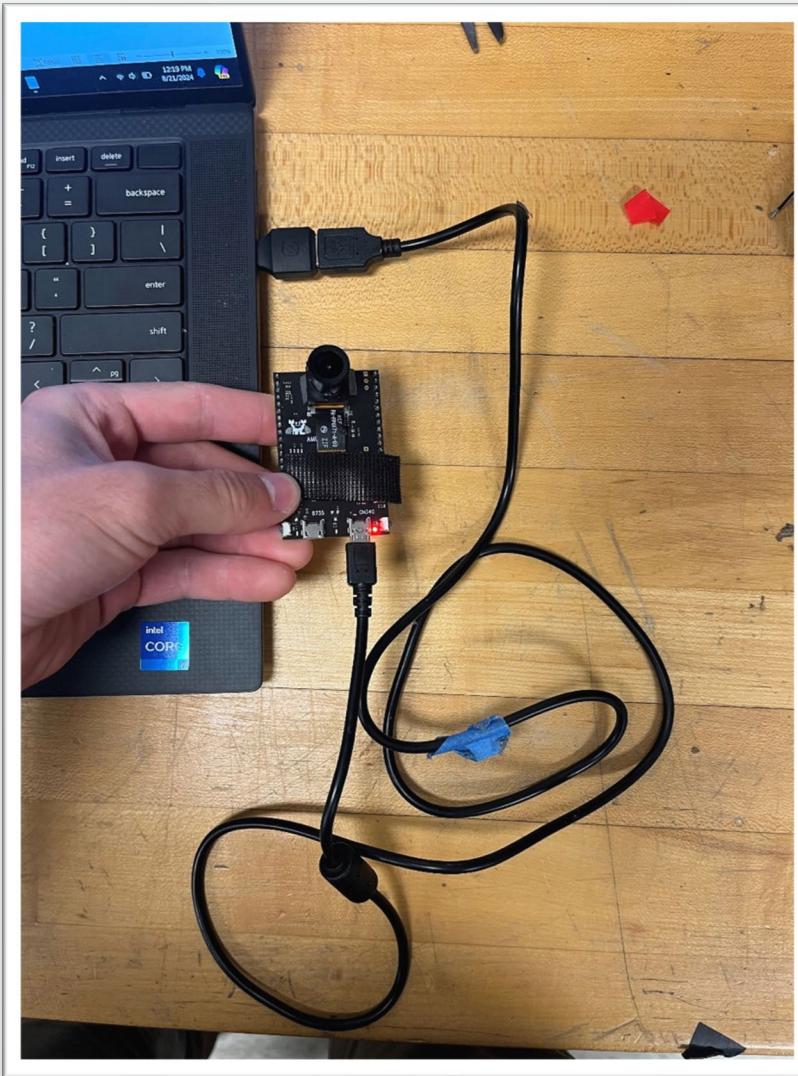


**Figure 91 Connect AMB 82 board with serial port cable**

If you have access to the Arduino programs in there .ino file form, go to the File dropdown and open one of the two programs, Figure 92. It does not matter which board each program goes onto, but after uploading, make sure each is labeled accordingly (this will be important with antenna positioning later). One program is called HIVE 2.1\_AP\_program and the other is HIVE2.1\_nonAP\_program.

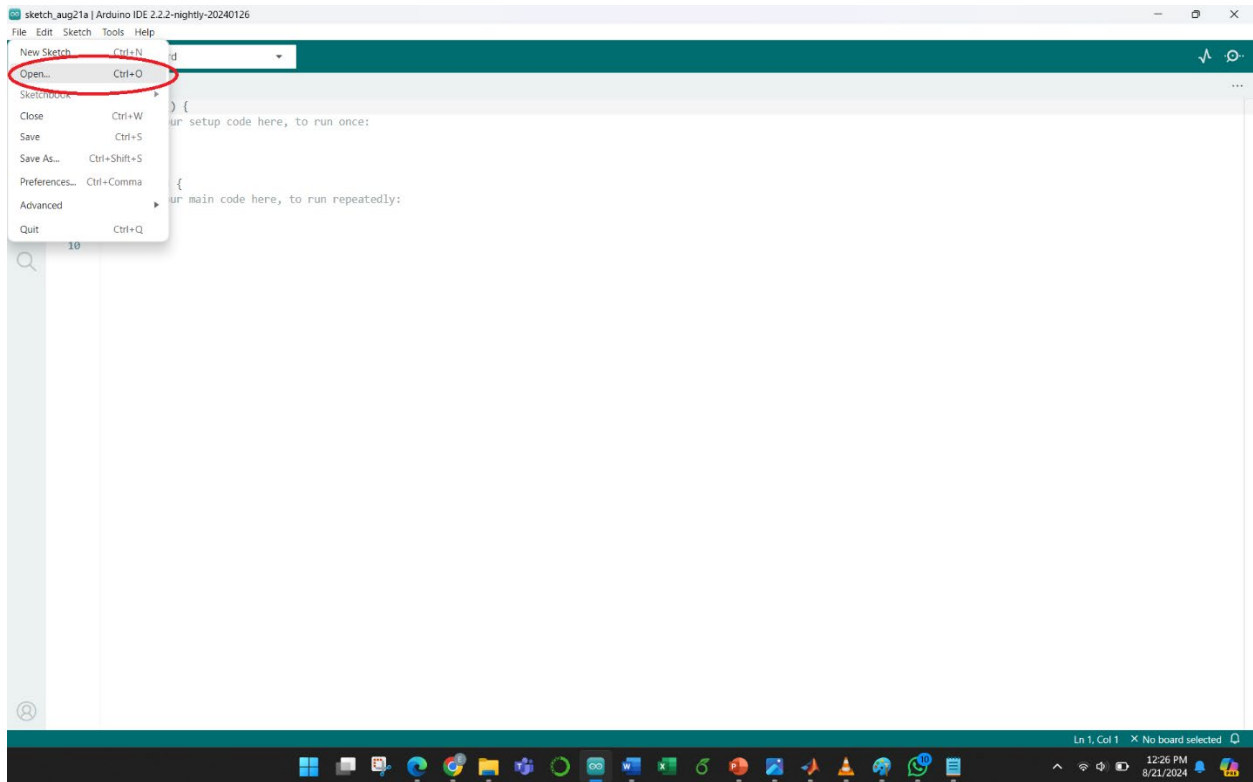


**Figure 92 Open Arduino program**

The full codes for both programs are listed below. If you do not have access to the files themselves, you can open Arduino IDE, delete every line of code on the screen, then copy and paste the entire code from each appendix below into Arduino IDE.

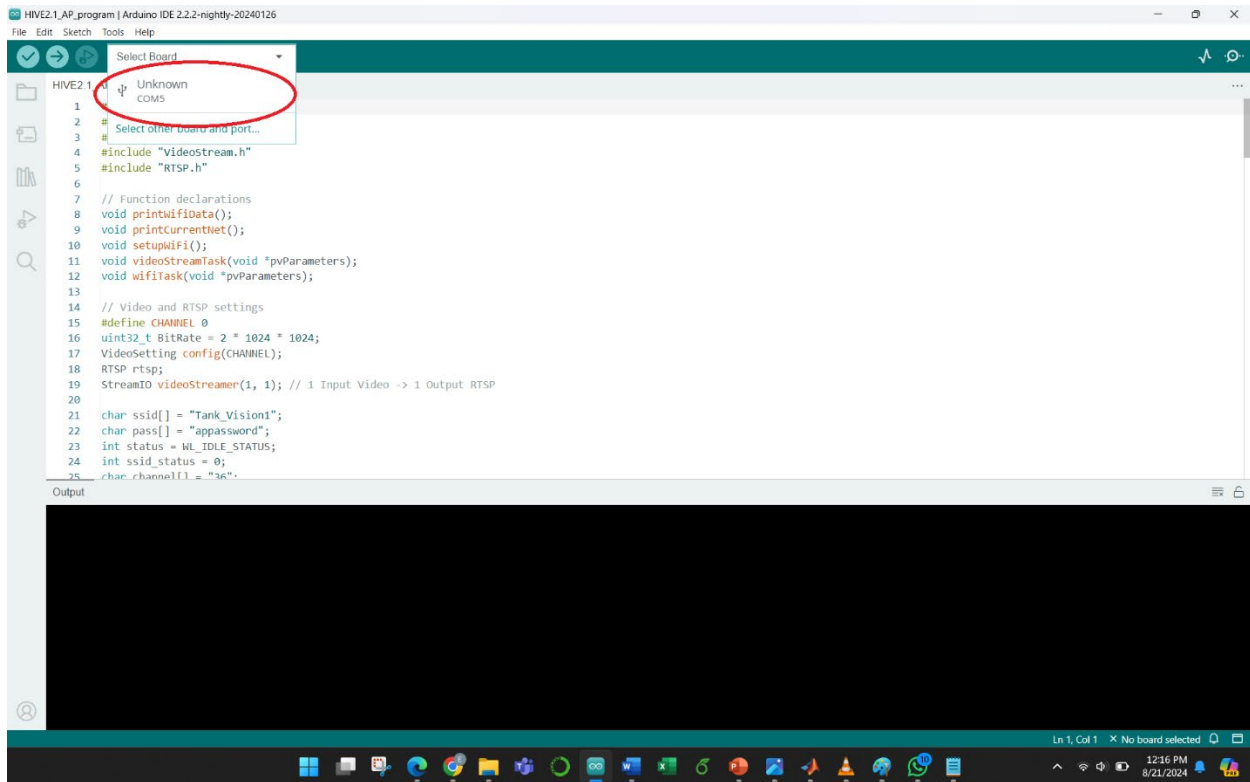


**Figure 93 Select Arduino board**

Once the board is plugged in and the program is opened, click the "Select board" dropdown and select the unknown board that appears. The board needs to be physically connected to your computer to work.

### Step 5: Enter Upload Mode

To allow code to be uploaded, the AMB needs to be in upload mode, Figure 94. This mode is active when the blue light by the thumb position is on. To activate this mode:

Press down the tiny button on the thumb side of the AMB and hold

While holding, press the pointer finger side button

Release the thumb button

If done in this order, the blue light should slowly turn on. This can sometimes take a couple of tries.

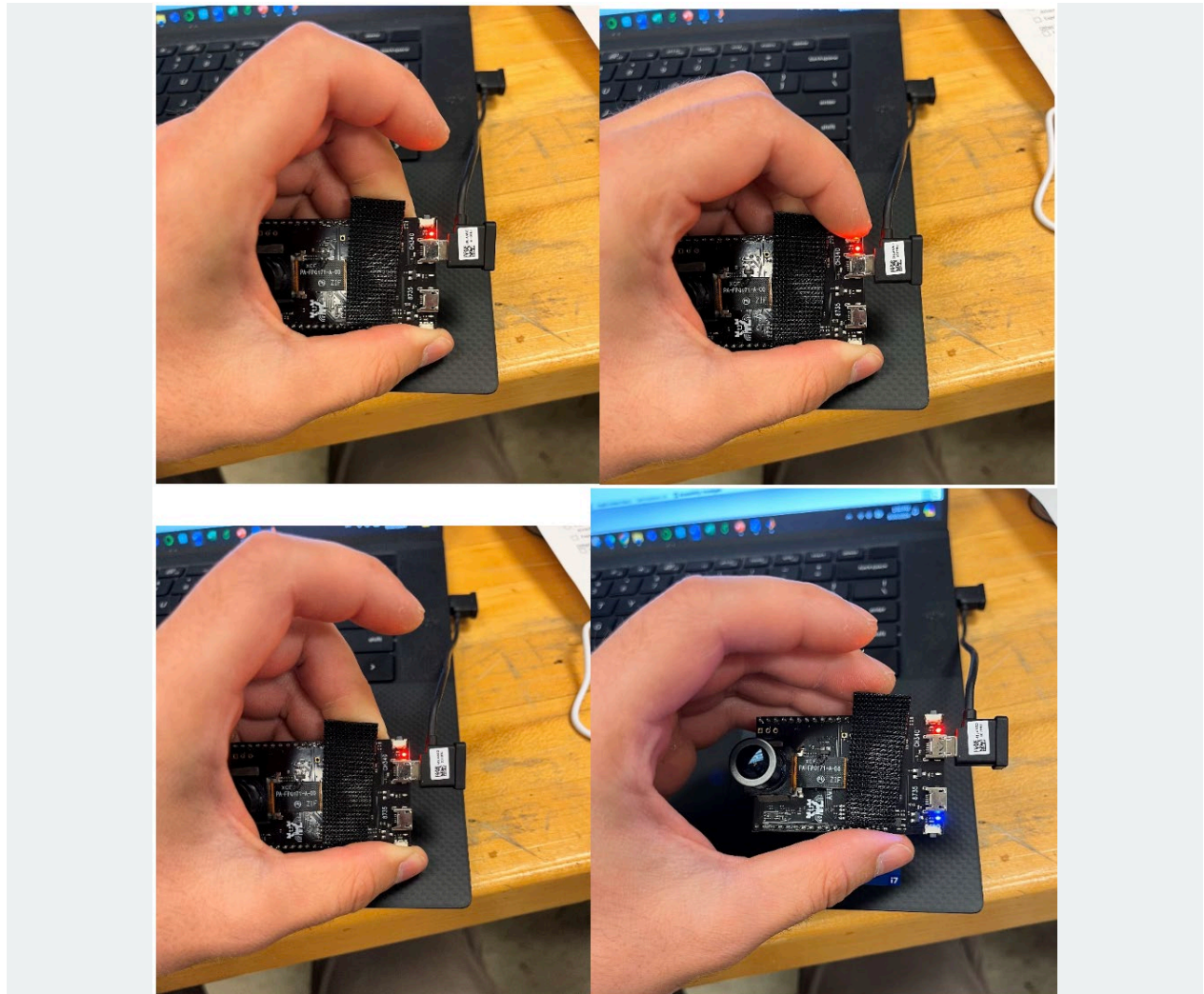


Figure 94 Activate upload mode on AMB 82

## Step 6: Upload the Code

Once the board is selected, press the "Upload" button in the top left (arrow-shaped icon shown in red). When the code is uploaded successfully, you should see a completion message at the bottom of the screen as outlined in red, Figure 95.

Repeat this upload process for the other AMB with the other program.

Important: Once these uploads are complete, the programs will be stored on the AMBs permanently and this part of the process will never need to be repeated. If the boards are not working later in the process, you can overwrite the current code by repeating these steps.

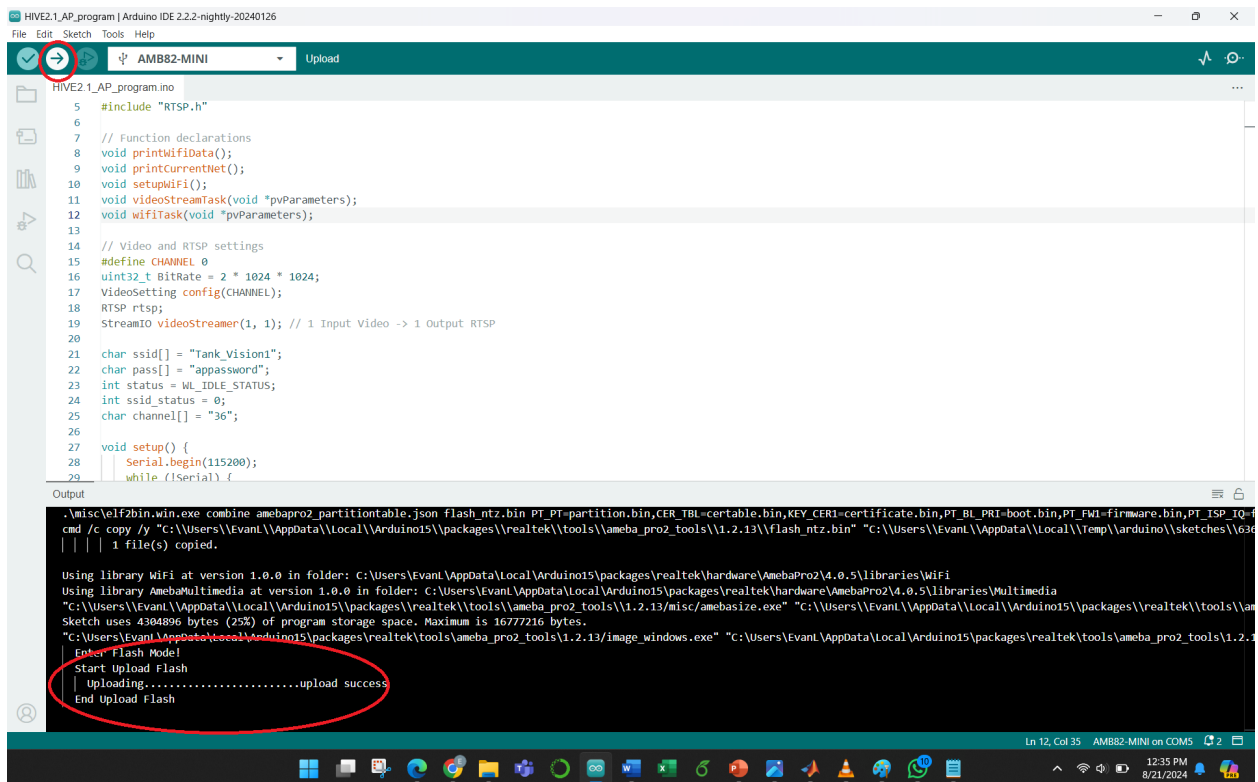


Figure 95 Upload the code

## Arduino Code for AMB Boards

The codes described below can be copy and pasted directly into an Arduino empty sketch. If you open Arduino software on your computer, you should be automatically in an empty sketch. Copy and paste the code directly into the sketch, you will need to do this twice for the different codes.

### AP Program Listing

```
#include <WiFi.h>

#include <FreeRTOS.h>
```

```

#include "StreamIO.h"
#include "VideoStream.h"
#include "RTSP.h"

// Function declarations
void printWifiData();
void printCurrentNet();
void setupWiFi();
void videoStreamTask(void *pvParameters);
void wifiTask(void *pvParameters);

// Video and RTSP settings
#define CHANNEL 0
uint32_t BitRate = 2 * 1024 * 1024;
VideoSetting config(CHANNEL);
RTSP rtsp;
StreamIO videoStreamer(1, 1); // 1 Input Video -> 1 Output RTSP

char ssid[] = "Tank_Vision_41/42";
char pass[] = "apassword";
int status = WL_IDLE_STATUS;
int ssid_status = 0;
char channel[] = "36";

void setup() {
    Serial.begin(115200);
    while (!Serial) {
        ; // Wait for serial port to connect. Needed for native USB port only
    }

    // Initialize WiFi task
    xTaskCreate(wifiTask, "WiFi Task", 4096, NULL, 1, NULL);

```

```

// Initialize video streaming task
xTaskCreate(videoStreamTask, "Video Stream Task", 4096, NULL, 1, NULL);
}

void loop() {
    // Main loop can remain empty or handle other tasks
}

void wifiTask(void *pvParameters) {
    while (true) {
        // Attempt to start AP
        Serial.println("Attempting to start AP with SSID: " + String(ssid));
        status = WiFi.apbegin(ssid, pass, channel, ssid_status);
        delay(10000); // Wait for AP to start

        if (status == WL_CONNECTED) {
            Serial.println("AP mode started");
            printWifiData();
            printCurrentNet();

            // Start WiFi connection task
            setupWiFi();
            vTaskDelete(NULL); // Delete this task
        } else {
            Serial.println("AP mode failed, retrying...");
            delay(10000);
        }
    }
}

void setupWiFi() {
    while (status != WL_CONNECTED) {
        Serial.print("Attempting to connect to WPA SSID: ");
    }
}

```

```

    Serial.println(ssid);
    status = WiFi.begin(ssid, pass);
    delay(2000);
}

Serial.println("Connected to WiFi");
printWifiData();
printCurrentNet();

// Configure camera video channel with video format information
config.setBitrate(BitRate);
Camera.configVideoChannel(CHANNEL, config);
Camera.videoInit();

// Configure RTSP with video format information
rtsp.configVideo(config);
rtsp.begin();

videoStreamer.registerInput(Camera.getStream(CHANNEL));
videoStreamer.registerOutput(rtsp);
if (videoStreamer.begin() != 0) {
    Serial.println("StreamIO link start failed");
}

Camera.channelBegin(CHANNEL);
printlnInfo();

vTaskDelete(NULL); // Delete WiFi setup task after completion
}

void videoStreamTask(void *pvParameters) {
    while (true) {
        if (status == WL_CONNECTED) {

```

```

    if (videoStreamer.begin() != 0) {
        Serial.println("StreamIO link start failed");
    }

    // Stream video data to RTSP
    Camera.channelBegin(CHANNEL);
    Serial.println("Video stream started");
    vTaskDelete(NULL); // Delete video stream task after completion
}
vTaskDelay(1000 / portTICK_PERIOD_MS);
}
}

```

```

void printWifiData() {
    IPAddress ip = WiFi.localIP();
    Serial.print("IP Address: ");
    Serial.println(ip);
    IPAddress subnet = WiFi.subnetMask();
    Serial.print("NetMask: ");
    Serial.println(subnet);
    IPAddress gateway = WiFi.gatewayIP();
    Serial.print("Gateway: ");
    Serial.println(gateway);
    Serial.println();
}

```

```

void printCurrentNet() {
    Serial.print("SSID: ");
    Serial.println(WiFi.SSID());
    byte bssid[6];
    WiFi.BSSID(bssid);
    Serial.print("BSSID: ");
    for (int i = 0; i < 6; i++) {

```

```

        Serial.print(bssid[i], HEX);
        if (i < 5) Serial.print(":");
    }
    Serial.println();
    byte encryption = WiFi.encryptionType();
    Serial.print("Encryption Type: ");
    Serial.println(encryption, HEX);
    Serial.println();
}

void printInfo(void) {
    Serial.println("-----");
    Serial.println("- Summary of Streaming -");
    Serial.println("-----");
    Camera.printInfo();

    IPAddress ip = WiFi.localIP();
    Serial.println("- RTSP -");
    Serial.print("rtsp://");
    Serial.print(ip);
    Serial.print(":");
    rtsp.printInfo();
}

```

### Non-AP Program Listing

/\*

Please adjust VideoSetting to get better video quality when streaming to V7RC APP:

```
VideoSetting config(VIDEO_D1, CAM_FPS, VIDEO_H264, 0);
```

Example guide:

<https://www.amebaiot.com/en/amebapro2-arduino-video-rtsp/>

\*/

```

#include "WiFi.h"
#include "StreamIO.h"
#include "VideoStream.h"
#include "RTSP.h"

#define CHANNEL 1

// Default preset configurations for each video channel:
// Channel 0 : 1920 x 1080 30FPS H264
// Channel 1 : 1280 x 720 30FPS H264
// Channel 2 : 1280 x 720 30FPS MJPEG

VideoSetting config(CHANNEL);
RTSP rtsp;
StreamIO videoStreamer(1, 1); // 1 Input Video -> 1 Output RTSP

char ssid[] = "Tank_Vision1"; // your network SSID (name)
char pass[] = "appassword";    // your network password
int status = WL_IDLE_STATUS;

void setup() {
    Serial.begin(115200);

    // attempt to connect to Wifi network:
    while (status != WL_CONNECTED) {
        Serial.print("Attempting to connect to WPA SSID: ");
        Serial.println(ssid);
        status = WiFi.begin(ssid, pass);

        // wait 2 seconds for connection:
        delay(2000);
    }
}

```

```

// Configure camera video channel with video format information
// Adjust the bitrate based on your WiFi network quality
config.setBitrate(1 * 1024 * 1024); // Recommend to use 2Mbps for RTSP streaming to prevent
network congestion
Camera.configVideoChannel(CHANNEL, config);
Camera.videoInit();

// Configure RTSP with identical video format information
rtsp.configVideo(config);
rtsp.begin();

// Configure StreamIO object to stream data from video channel to RTSP
videoStreamer.registerInput(Camera.getStream(CHANNEL));
videoStreamer.registerOutput(rtsp);
if (videoStreamer.begin() != 0) {
    Serial.println("StreamIO link start failed");
}

// Start data stream from video channel
Camera.channelBegin(CHANNEL);

delay(1000);
printlnInfo();
}

void loop() {
    // Do nothing
}

void printlnInfo(void) {
    Serial.println("-----");
    Serial.println("- Summary of Streaming -");
    Serial.println("-----");
}

```

```
Camera.printlnInfo();

IPAddress ip = WiFi.localIP();

Serial.println("- RTSP -");
Serial.print("rtsp://");
Serial.print(ip);
Serial.print(":");
rtsp.printlnInfo();
}
```

## Appendix B: Build Instructions for the HIVE 3.0

### B.1 Materials

The following is an overview of the hardware used to assemble various configurations of a HIVE 3.0. The HIVE comes in three configurations: one leader configuration (manual control) and two follower configurations (autonomous): smart and basic. The smart-follower configuration utilizes depth imaging of the environment, which enables obstacle avoidance even in low to no light and can be used for mapping. The basic-follower configuration has only an RGB camera which significantly reduces cost, and with the current software, limits functionality to following obstacle-free paths only. It is possible to implement an obstacle detection algorithm such as You Only Look Once (YOLO) to achieve obstacle detection and avoidance with only flat images.

### B.2 Standard Components

The HIVE 3.0 operates on the same chassis as the HIVE 2.0 and 2.1 – the Heng Long RC Sherman Tank. This hobby vehicle is sold in two models: the base model, which uses a plastic gearbox and plastic treads and the S model, which uses both a metal gearbox and metal treads. The plastic treads and gears proved in testing to be too fragile. The metal gears and treads proved to be sufficiently robust to operate in the culvert environment. Table 9 outlines the other essential components of a HIVE 3.0, which total \$367.80. Prices for the HIVE 3.0 are from April 2025.

**Table 9 HIVE 3.0 standard components**

| Item                           | Qty | Unit Price [\$] | Total Price [\$] |
|--------------------------------|-----|-----------------|------------------|
| Heng Long RC Sherman Tank      | 1   | 229.99          | 229.99           |
| Low Cost Motor Actuator (LCMA) | 1   | 14.40           | 14.40            |
| AMB82-mini                     | 1   | 23.99           | 23.99            |
| XBee S2C RF module             | 1   | 29.33           | 29.33            |
| Micro LED spotlight            | 1   | 7.04            | 7.04             |
| Encoder housing                | 1   | 12.60           | 12.60            |
| Tank shell                     | 1   | 50.45           | 0.45             |
| Total Base Price               | N/A | N/A             | 367.80           |

The AMB82-mini is a development board used to live-stream video feeds from the HIVE to the user. Its technical specifications are highlighted in Table 10.

**Table 10 AMB82-mini technical specifications (Realtek 2025b).**

| Category  | Description              |
|-----------|--------------------------|
| Processor | ARMv8M@500MHz            |
| Memory    | DDR2 128MB Micro SD slot |

|               |                                                                  |
|---------------|------------------------------------------------------------------|
| Communication | 2.4 GHz and 5.0 GHz IEEE 802.11 a/b/g/n, Bluetooth 5.1 BLE       |
| IO            | 2 USB 3.0 ports, 30-pin GPIO header                              |
| Power         | 5V DC input via USB-micro connector, 5V DC input via GPIO header |
| Dimensions    | 60mm × 40mm × 15mm                                               |
| Camera        | 130° × 80° FOV, 1920 × 1080 resolution at 30fps                  |
| Cost          | \$23.99                                                          |

The XBee S2C is an RF module used to relay control signals to the HIVE leader unit. The design supports various network architectures between many modules. Technical specifications of the XBee are highlighted in Table 11

**Table 11 XBee S2C technical specifications (Digi 2024)**

| Category      | Description                                                  |
|---------------|--------------------------------------------------------------|
| Communication | 2.4 GHz IEEE 802.15.4, 60m indoor range, 1200m outdoor range |
| IO            | 20-pin GPIO header                                           |
| Power         | 2.1-3.6V DC input via GPIO header                            |
| Dimensions    | 27mm × 24mm × 10mm                                           |
| Cost          | \$29.33                                                      |

### B.3 Leader Components

A custom wireless controller controls the HIVE leader. Table 12 outlines the components required to assemble the controller.

**Table 12 Components for remote control.**

| Item                      | Qty | Unit Price [\$] | Total Price [\$] |
|---------------------------|-----|-----------------|------------------|
| 3.7V 2500mAh LiPo battery | 1   | 11.99           | 11.99            |
| Joystick                  | 1   | 0.99            | 0.99             |
| Arduino Nano              | 1   | 3.79            | 3.79             |
| XBee S2C RF module        | 1   | 29.33           | 29.33            |
| Power switch              | 1   | 0.40            | 0.40             |
| Enclosure                 | 1   | 10.69           | 10.69            |
| M3x12 bolt                | 8   | 0.07            | 0.56             |
| M3 nut                    | 8   | 0.03            | 0.24             |
| Total Cost                | N/A | N/A             | 57.99            |

## B.4 Follower Components

Both HIVE follower configurations require rotary encoders and coupling gears for wheel speed feedback, as well as a Raspberry Pi for image processing, control algorithm computation, and communication with the LCMA. Table 13 lists key technical specifications of the Raspberry Pi 4.

The smart follower requires the components in Table 14 and in Table 15 as well as a RealSense D435i (Figure 96), which is a color and depth camera that uses stereoscopic depth estimation to produce depth images of the environment and aligns these with color images captured simultaneously. Table 16 lists technical specifications for the RealSense D435i.

**Table 13 Raspberry Pi 4B technical specifications (Raspberry Pi 2025)**

| Category      | Description                                                                    |
|---------------|--------------------------------------------------------------------------------|
| Processor     | Broadcom BCM2711, quad-core Cortex-A72, (ARM v8) 64-bit SoC @ 1.5GHz           |
| Memory        | Up to 8GB LPDDR4 RAM, Micro SD slot                                            |
| Communication | 2.4 GHz and 5.0 GHz IEEE 802.11b/g/n/ac<br>Bluetooth 5.0 BLE, Gigabit Ethernet |
| IO            | 2 USB 3.0 ports, 3 USB 2.0 ports, 40-pin GPIO header, 2 micro HDMI ports       |
| Power         | 5V DC input via USB-C connector, 5V DC input via GPIO header                   |
| Dimensions    | 85mm × 56mm × 15mm                                                             |
| Cost          | \$45.00                                                                        |

**Table 14 Additional components for the basic follower**

| Item              | Qty        | Unit Price [\$] | Total Price [\$] |
|-------------------|------------|-----------------|------------------|
| Rotary Encoder    | 2          | 18.99           | 37.98            |
| 33T 0.6M Gear     | 2          | 11.57           | 23.14            |
| Raspberry Pi 4B   | 1          | 45.00           | 45.00            |
| <b>Total Cost</b> | <b>N/A</b> | <b>N/A</b>      | <b>\$106.12</b>  |

**Table 15 Additional components for the smart follower**

| Item              | Qty        | Unit Price [\$] | Total Price [\$] |
|-------------------|------------|-----------------|------------------|
| Rotary Encoder    | 2          | 18.99           | 37.98            |
| 33T 0.6M Gear     | 2          | 11.57           | 23.14            |
| Raspberry Pi 4B   | 1          | 45.00           | 45.00            |
| RealSense D435i   | 1          | 334.00          | 334.00           |
| <b>Total Cost</b> | <b>N/A</b> | <b>N/A</b>      | <b>\$440.12</b>  |

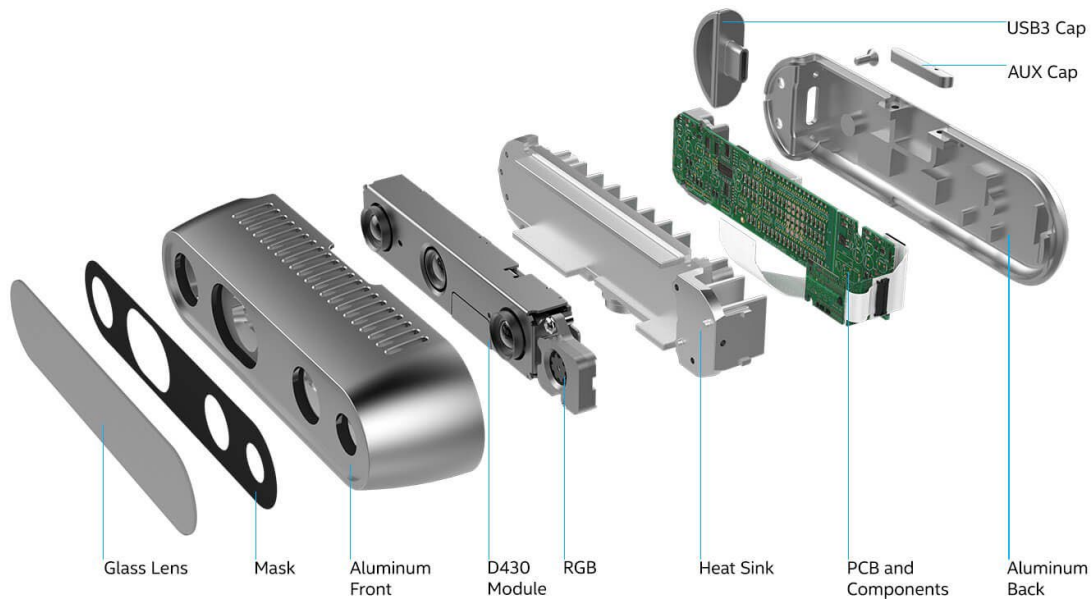


Figure 96 Exploded view of Intel RealSense D435i components (RealSense 2025)

**Table 16 Intel RealSense D435i technical specifications (RealSense 2025).**

| Category | Item                 | Specification           |
|----------|----------------------|-------------------------|
| Depth    | Depth Technology     | Stereoscopic estimation |
| Depth    | Depth FOV            | 87° × 58°               |
| Depth    | Output resolution    | Up to 1280 × 720        |
| Depth    | Frame rate           | Up to 90 FPS            |
| Depth    | Depth Accuracy       | > 98%                   |
| RGB      | RGB FOV              | 69° × 42°               |
| RGB      | Frame rate           | Up to 30 FPS            |
| RGB      | Shutter technology   | Rolling shutter         |
| Physical | Length Width, Height | 90 mm × 25 mm × 25      |
| Cost     | N/A                  | N/A                     |

## B.5 Chassis Disassembly

Begin with a stock Heng Long 1/16 Scale USA M4A3 Sherman Battle Tank, the base vehicle adopted for the HIVE 2.0.

Before installing new electronics, all stock electronics must be stripped out of the tank.

Remove the 8 Phillips screws from the bottom of the tank (Figure 97):

4 top screws (circled red),

2 glacis plate screws (circled orange),

1 battery compartment screw (circled yellow),

1 smoke module screw (circled green).

Open the battery compartment, disconnect the battery, and set aside.

Remove the top of the tank, revealing the stock control board (Figure 98).

Remove all JST and header connectors from the control board. Figure 99 shows the control board with all connectors removed.

Remove the top half of the tank.

Cut the motor and battery wires near their connections to the control board highlighted in Figure 99 and remove the board.

Remove the smoke tubes and smoke module (Figure 100).

Remove 2 switch plate screws and free the switch plate (Figure 101).

Remove the switch plate and switch wires.

Remove the two remaining glacis plate screws and the glacis plate (Figure 102).

Remove the TK-7x mounting plate.

The fully stripped chassis is shown in Figure 103. All that remains in the chassis cavity are 3 pairs of wires: 2 pairs for the left and right motors, 1 pair for the battery.

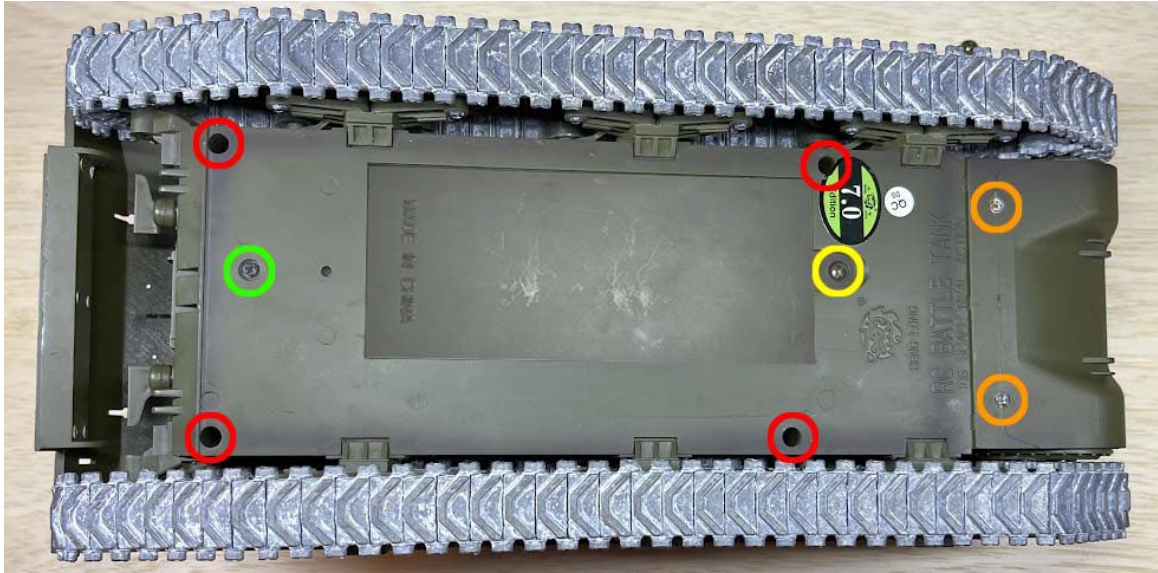


Figure 97 Screws to remove on bottom of Heng Long Sherman tank (Gamble 2025a)

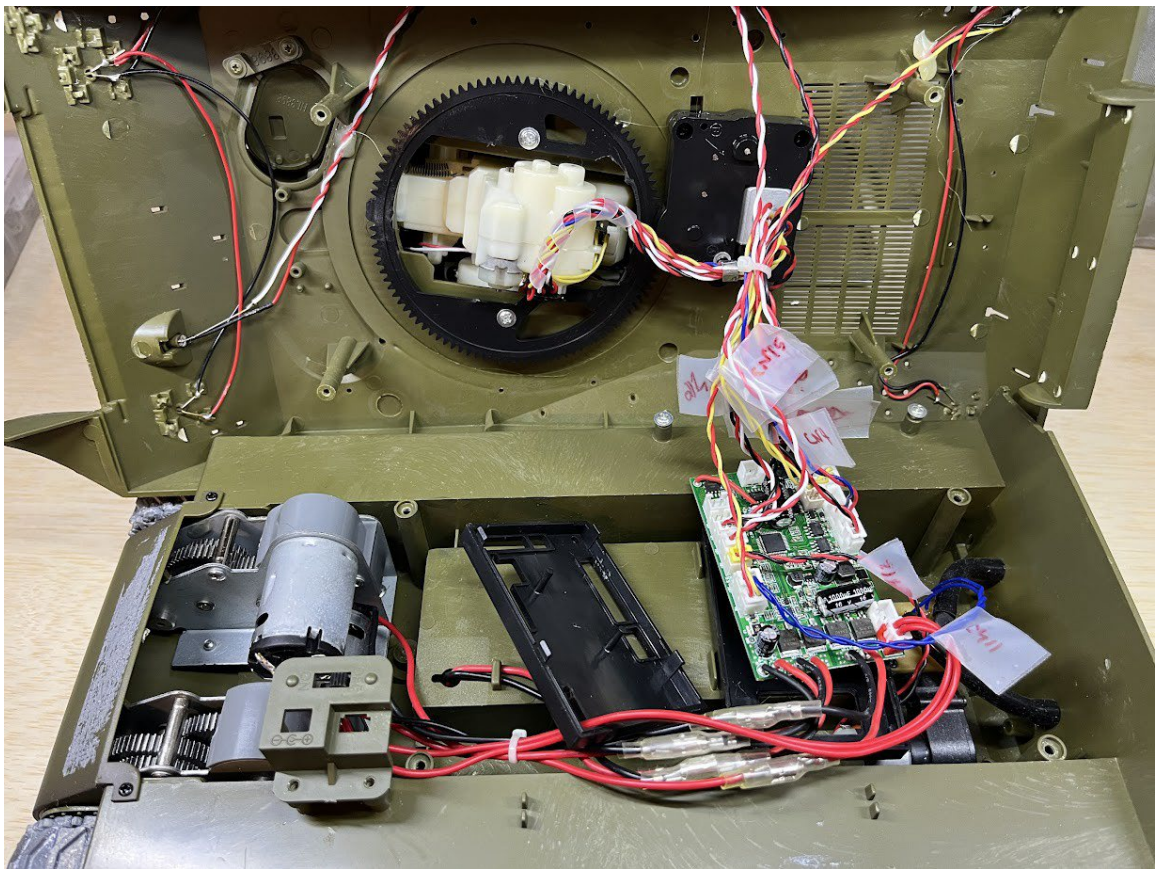


Figure 98 Inside view of tank (stock configuration) (Gamble 2025a)



Figure 99 Soldered power connections to cut on stock control board (Gamble 2025a)

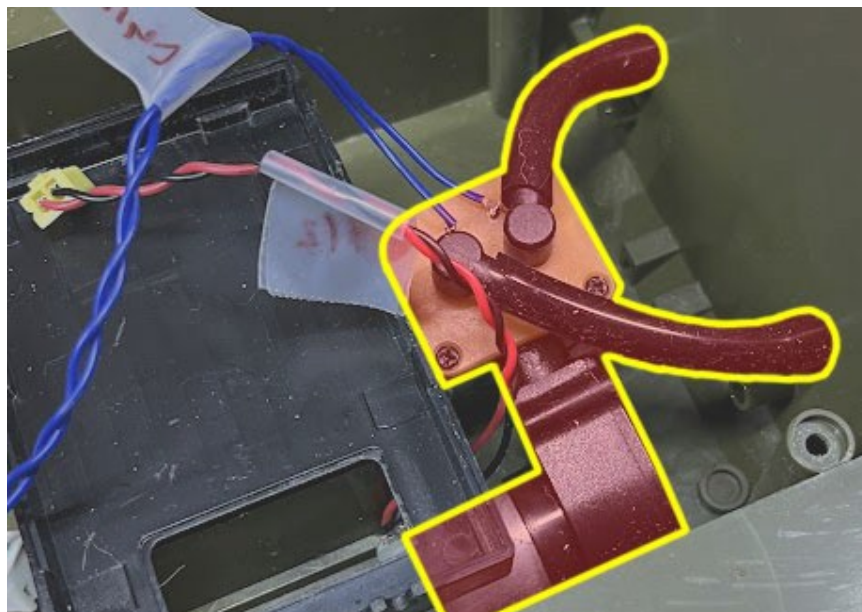


Figure 100 Smoke tubes and module to remove (Gamble 2025a)

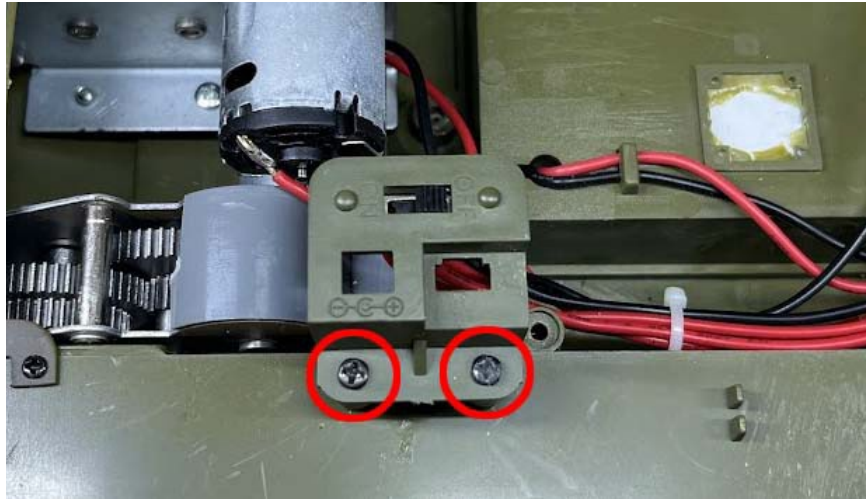


Figure 101 Switch plate screws to remove (Gamble 2025a)

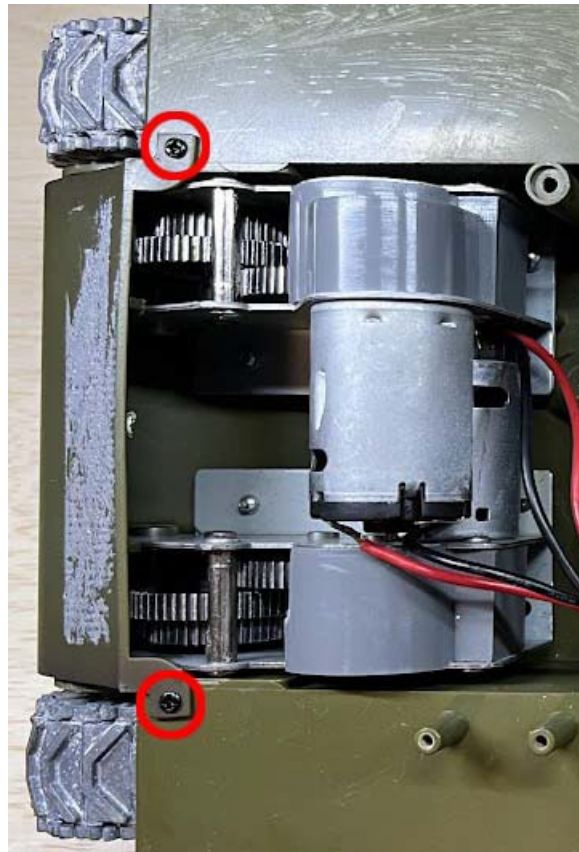


Figure 102 Glacis plate top screws to remove (Gamble 2025a)

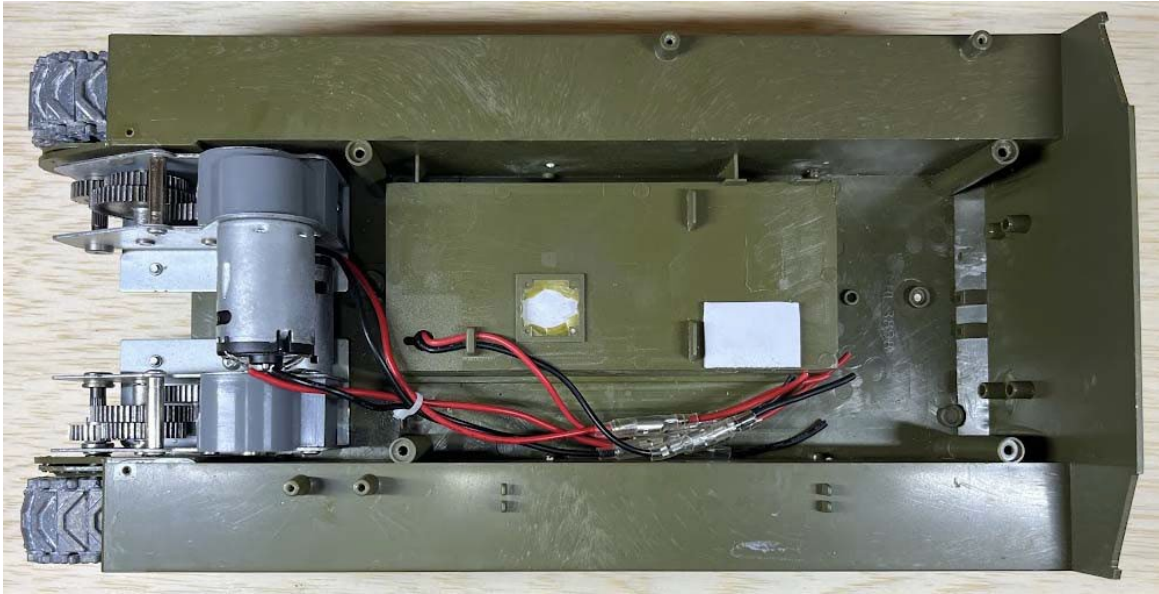


Figure 103 Tank fully stripped of stock electronics. (Gamble 2025a)

## B.6 Install Connectors on Power Wires

Remove main tank battery if not already removed.

Strip 4mm of sheathing off the 6 power wires remaining in the chassis: left motor positive and negative, right motor positive and negative, battery positive and negative.

Install JST crimp connectors on each wire.

Take the left motor positive and negative wires and slide the crimp connectors into the 2 pin JST XH 2.54 mm male terminal, orienting the positive (red) and negative (black) as shown in Figure 104.

Repeat for the right motor wire pair and battery wire pair.

## B.7 Prepare and Install Encoders

The encoders have 4 wires and a braided shielding in the main cable. Red and black are positive and negative, respectively. White and green are out-of-phase signal wires.

Cut the encoder main cable to a length of 40 cm.

Strip off 2 cm of the main sheathing.

Trim away the braided sheathing, paper sheathing, and white wire.

Strip 4mm off the red, black, and green inner wires.

Install JST crimp connectors on the stripped wires.

Slide the crimp connectors into the 3 pin JST XH 2.54 mm male terminal, orienting as shown in Figure 105.

Bore out the 33T 0.6M gear to 6mm to accommodate the encoder shaft.

Insert the left encoder into the encoder housing. Secure the encoder using three M3x8 bolts and washers (Figure 106).

Secure the right encoder using three M3x12 bolts and washers (Figure 107).

Attach the 33T 0.6M gears to the encoder shafts (Figure 108).

Slide the encoder housing onto the front of the tank and secure with screws using the same four holes used for the stock glacis plate.

Adjust the encoder gear shaft positions to be in-line and meshing with the appropriate gear train gears. Tighten in position using the 2 mm set screw. Figure 109 shows the left gear being shifted into alignment.

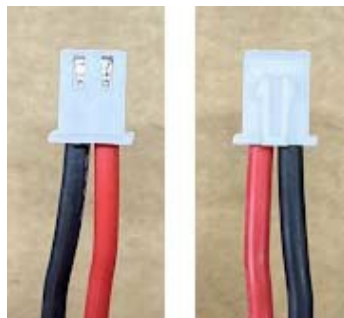


Figure 104 Orientation of power wires in 2-pin JST XH connector (Gamble 2025a)

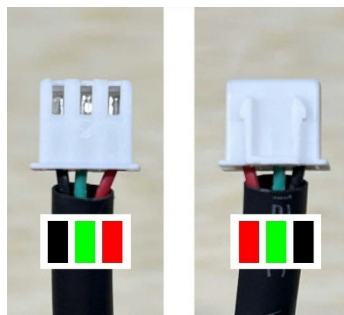


Figure 105 Orientation of power and signal wires of encoder in 3-pin JST XH connector. (Gamble 2025a)



Figure 106 Left encoder secured in housing (Gamble 2025a)



Figure 107 Right encoder secured in housing. (Gamble 2025a)

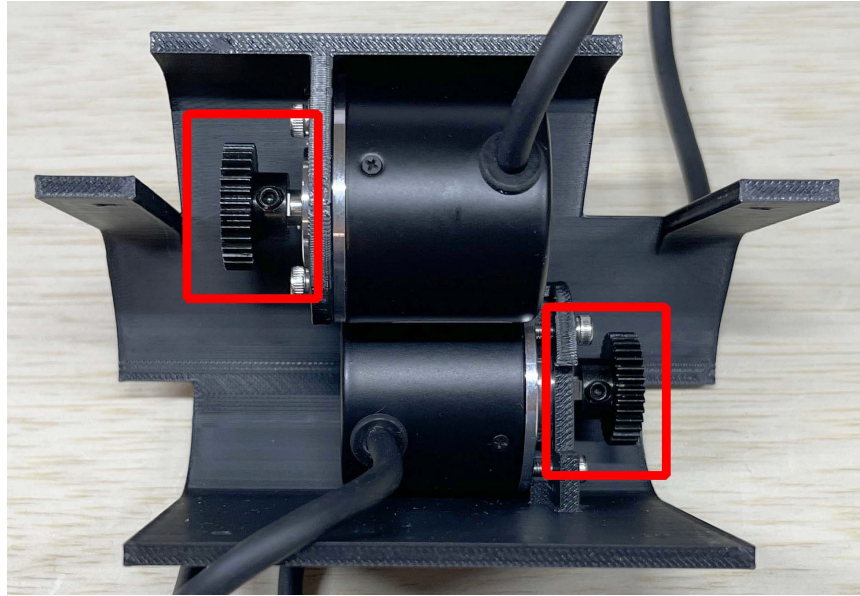


Figure 108 Encoders in housing with gears attached. (Gamble 2025a)

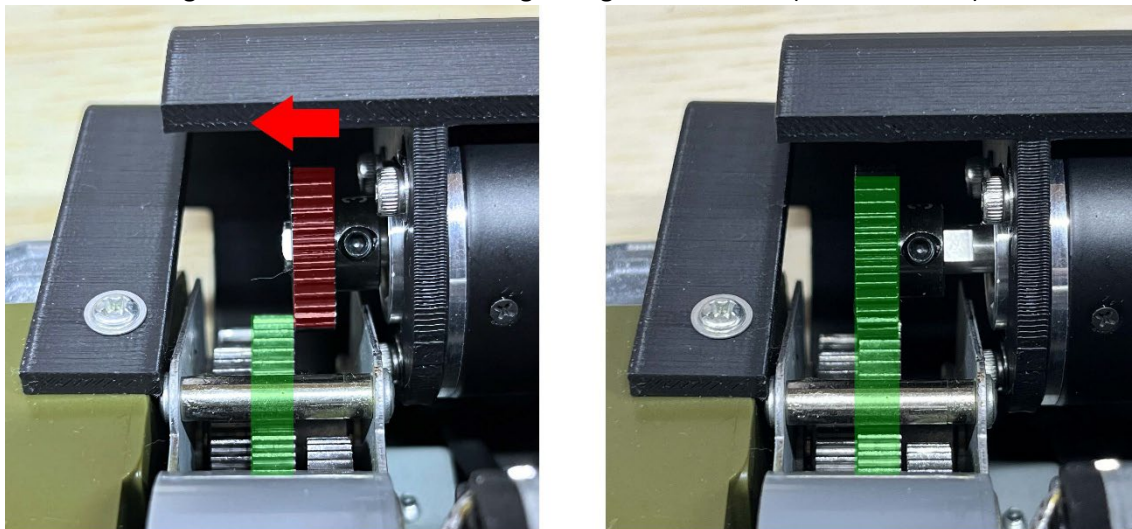


Figure 109 Left encoder gear adjustment: Left - encoder gear out of alignment with gear train; Right - encoder gear shifted into alignment with gear train. (Gamble 2025a)

## B.8 Install LCMA and Raspberry Pi

The Low Cost Motor Actuator (LCMA) is a custom ATMEGA-based microcontroller board used for motor control. The LCMA is adaptable to any differential drive vehicle.

Refer to Figure 33 for LCMA connector information.

1. Connect the left and right encoder cables to the LCMA.
2. Connect the left and right motor cables to the LCMA.

3. Connect the motor battery cable to the LCMA.
4. Connect the Raspberry Pi to the LCMA via USB. Ensure that the serial communication switch is toggled to USB.

## B.9 Install Shell

The shell protects the internal electronics as well as providing a location to mount the RealSense camera.

1. Using two M3x6 bolts, attach the RealSense to its mounting point in the shell (Figure 110).
2. Attach the 90-degree USB-C between the RealSense and Raspberry Pi.
3. Connect the portable battery to the Raspberry Pi.



Figure 110 Underside of shell with RealSense mounted. Mounting screws highlighted (Gamble 2025a)

At this point, the electronics are all connected. Figure 111 shows an overview of all cable connections that should be made at this point. With all connections made and checked, the shell is ready to be attached, enclosing the electronics.

1. Align the shell to be flush with the the chassis flange and top edge of encoder housing, highlighted in Figure 111.
2. Attach the shell to the chassis using the original 4 screws and screw locations of the stock shell.

Figure 10 shows the HIVE 3.0 with both the shell and encoder housing installed.

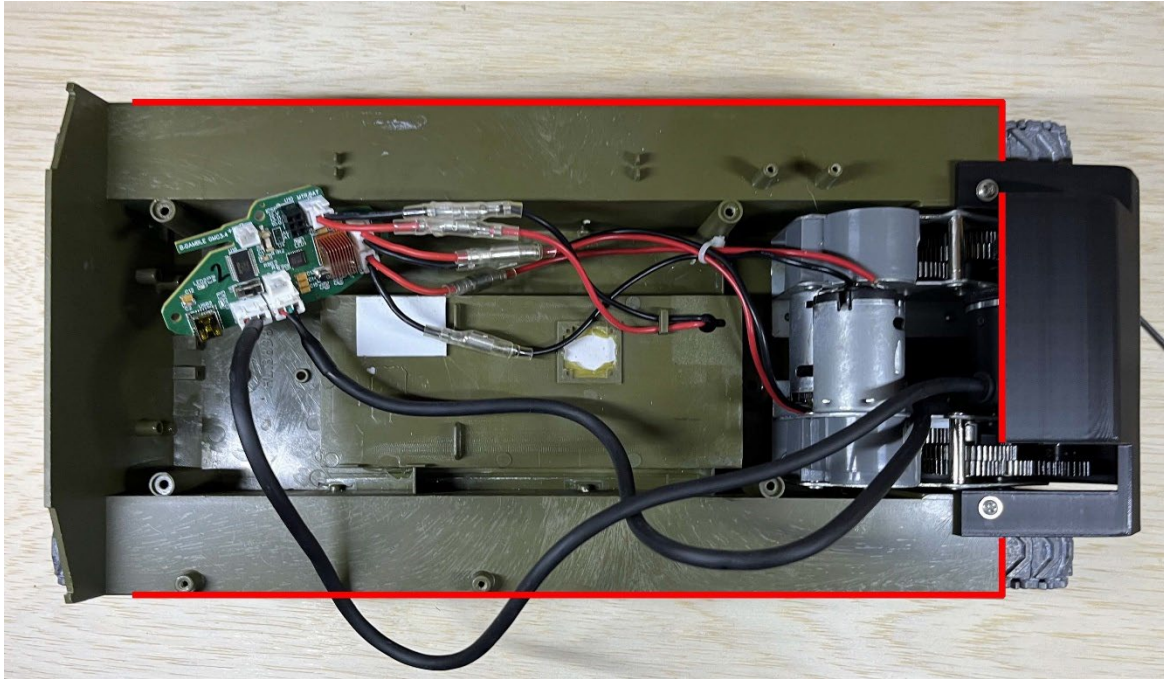


Figure 111 Alignment guide for attaching the shell to the chassis. (Gamble 2025a)

## B.10 LCMA Design

A component-populated CAD model of the LCMA is shown in Figure 112 and Figure 113.

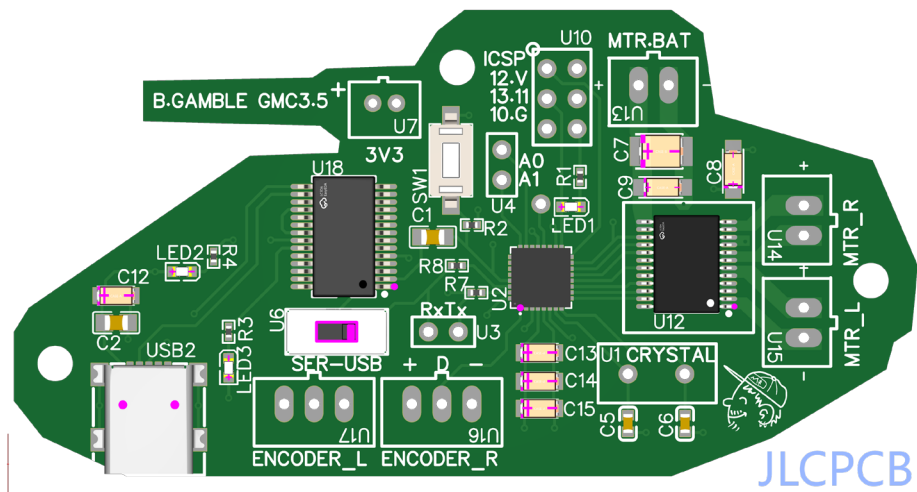


Figure 112 GMC PCB top side. (Gamble 2025a)

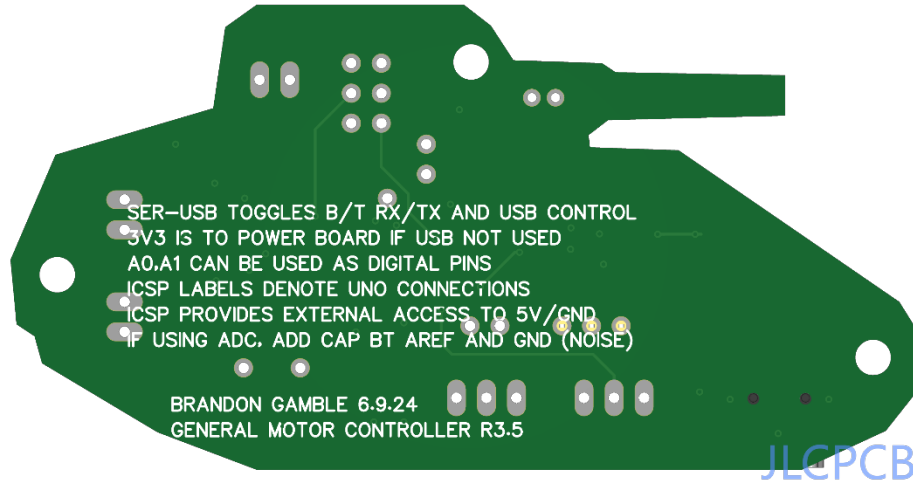


Figure 113 GMC PCB bottom side (Gamble 2025a)

## Appendix C: HIVE 4.0

At the time of this report, the HIVE 4.0 remains a work in progress. Figure **114** shows the HIVE 4.0 chassis. Figure 115 shows the HIVE 4.0 with electronic controls and telemetry.

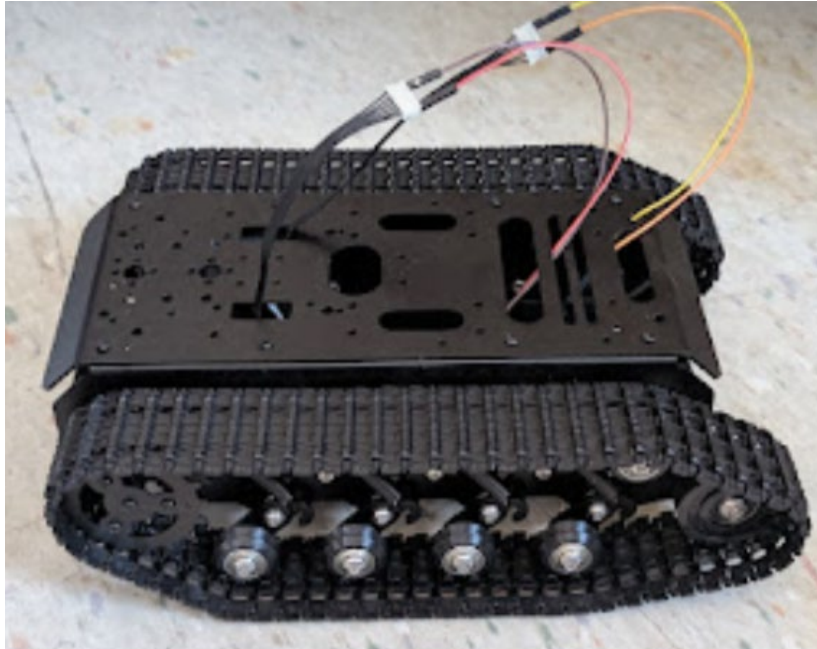


Figure 114 HIVE 4.0 chassis

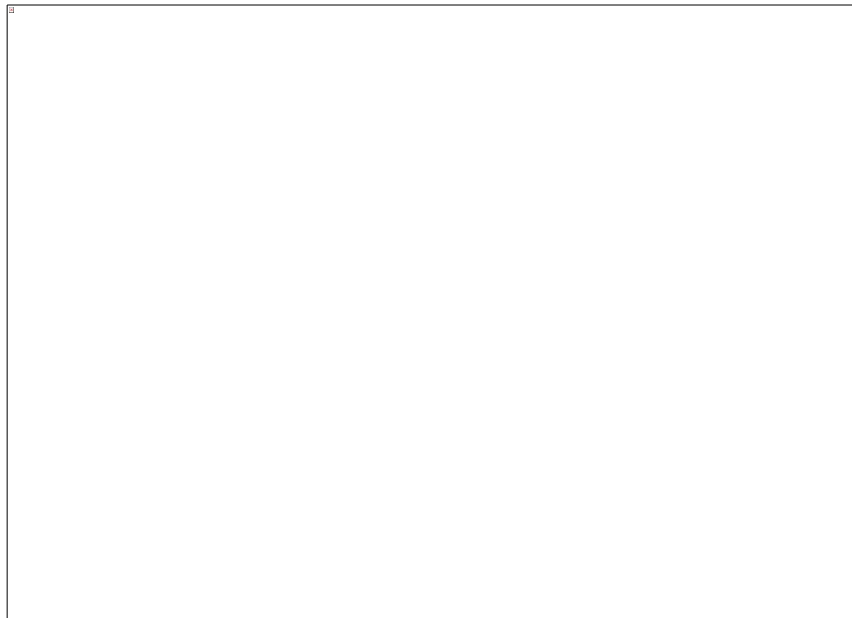


Figure 115. HIVE 4.0 with electronic controls and telemetry

## Appendix D: HIVE Building Workshop at VAOT

The HIVE 2.1 design progressed to the stage where it was decided to put on a workshop for Vermont Agency of Transportation personnel to learn how to build and operate HIVE 2.1s. The workshop was held at the Dill Building in Barre, VT on Dill Building on January 21, 2026. Eight teams of approximately 25 people total from the various maintenance districts participated, built and took home functioning HIVE 2.1 robots.



Figure 116 Building HIVE 2.1 by modifying hobby Sherman tank



**Figure 117 Building take-up reel assemblies**



**Figure 118 Waterproofing of HIVE 2.1 tank**