VERMONT
AGENCY OF TRANSPORTATION

Hydraulic Inspection Vehicle Explorer (HIVE) Culvert Upgrade

Dryver Huston, Professor

University of Vermont
Mechanical Engineering

Tian Xia, Professor

University of Vermont
Electrical and Biomedical Engineering

Jonathan Burton, Graduate Student

University of Vermont
Mechanical Engineering

Daniel Orfeo, Graduate Student

University of Vermont
Mechanical Engineering

April 2021

Research Project

Reporting on Project 19-3

Final Report 2021-01

The information contained in this report was compiled for the use of the Vermont Agency of Transportation. Conclusions and recommendations contained herein are based upon the research data obtained and the expertise of the researchers and are not necessarily to be construed as Agency policy. This report does not constitute a standard, specification, or regulation. The Vermont Agency of Transportation assumes no liability for its contents or the use thereof.

This material is based upon work supported by the Federal Highway Administration under SPR VTRC 19-3. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration.

TECHNICAL DOCUMENTATION PAGE

1. Report No.
2021-01

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Hydraulic Inspection Vehicle Explorer (HIVE) Culvert Upgrade

5. Report Date
May 11, 2021

6. Performing Organization Code

7. Author(s)
Huston, Dryver, ORCID 0000-0002-0957-0574; Xia, Tian, ORCID 0000-0002-4395-7350; Burton, Jonathan; Orfeo, Daniel

8. Performing Organization Report No.

9. Performing Organization Name and Address
Department of Electrical and Biomedical Engineering
The University of Vermont
33 Colchester Ave.
Burlington, VT 05405

10. Work Unit No.

11. Contract or Grant No.
VTRC 19-3

12. Sponsoring Agency Name and Address
Vermont Agency of Transportation (SPR)
Research Section
One National Life Drive
Montpelier, VT 05633

13. Type of Report and Period Covered
Final Report 2019-2021

14. Sponsoring Agency Code

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.
https://vtrans.vermont.gov/sites/aot/files/VTrans 19_3 Hive 2.0 Final Report 051121.pdf

The Vermont Agency of Transportation (VTrans) has adopted a policy requiring all culverts to be inspected every 5 years, resulting in around 9,600 small culverts needing to be inspected annually. Proper inspection of small culverts can prevent roadway failures, traffic disturbances, and save tens of thousands of dollars on costly repairs. Many of these culverts have small diameters that preclude human inspection. This report describes the design, fabrication and testing of a lightweight and low-cost culvert inspection vehicle known as the Hydraulic Inspection Vehicle Explorer 2.0 (HIVE 2.0). It is a tracked vehicle with a conceptual design inspired by an earlier generation HIVE based on a 4-wheel drive chassis and with a form factor chosen for maneuverability through small, flooded culverts. Improvements with the HIVE 2.0 include superior maneuverability across gaps in the culvert bed and increased video telemetry range through small culverts and drop inlets. Optimal settings for video transmission through small culverts are understood through theory and a series of field tests. Finally, performance for drop inlet inspection scenarios is characterized and discussed. Field tests confirm the capabilities of the HIVE 2.0.

The project objectives are: 1. Clarification of design requirements, 2. Identify test sites, 3. Design, build and field test prototype robot, 4. Change and improve robot based on field test results, 5. Fabricate and deliver functional robot, 6. Technology transfer, benefit quantification, and guidelines for implementation.

17. Key Words culvert, HIVE, hydraulic, inspection, robot, vehicle, wireless		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 111	**22. Price**

ABSTRACT

The Vermont Agency of Transportation (VTrans) has adopted a policy requiring all culverts to be inspected every 5 years, resulting in around 9,600 small culverts needing to be inspected annually. Many of these culverts have small diameters that preclude human inspection. This report describes the design, fabrication and testing of a lightweight and low-cost culvert inspection vehicle known as the Hydraulic Inspection Vehicle Explorer 2.0 (HIVE 2.0). It is a tracked vehicle with a conceptual design inspired by an earlier generation HIVE based on a 4-wheel drive chassis. Improvements with the HIVE 2.0 include superior maneuverability across gaps in the culvert bed and increased video telemetry range through small culverts and drop inlets (DIs). Field tests confirm the capabilities of the HIVE 2.0.

The project objectives are: 1. Clarification of design requirements, 2. Identify test sites, 3. Design, build and field test prototype robot, 4. Change and improve robot based on field test results, 5. Fabricate and deliver functional robot, 6. Technology transfer, benefit quantification, and guidelines for implementation.

ACKNOWLEDGMENTS

This work was funded by the Vermont Agency of Transportation (VTrans) under research project 19-3. Michelle Redmond was the VTrans Champion project, who along with Steven Stanley, also from VTrans, provided invaluable assistance to this project in terms technical guidance, feedback on proposed solutions and access to culverts for inspection. The VTrans Technical Advisory Committee (TAC) for the project also included Dr. Emily Parkany and Tanya Miller. The TAC helped with project supervision, planning, logistics, advice on technical directions and overall encouragement. Dr. Dylan Burns and Logan Griswold from the University of Vermont helped with the fabrication, testing and technology development for the HIVE 2.0. Many aspects of this report derive from the M.S. Thesis by Jonathan Burton [Burton 2020].

Table of Contents

1. INTRODUCTION

1.1 Overview

Culverts are structures which allow water to pass under roads, paths, or similar obstacles, i.e. “A culvert is a structure designed hydraulically to take advantage of submergence to increase water carrying capacity. Culverts, as distinguished from bridges, are usually covered with embankment and are composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert.” [Rossow 2012].

The failure of culverts can cause flooding, severe traffic disturbances, and roadway washouts or cave-ins. Many of these failures are progressive. They begin with small damage and distress that grows with time and environmental stress. Culvert inspections can identify signs of distress such as cracks, separations, and holes at early stages of developments before larger failures take place. Damaged culverts can be repaired quickly, cost effectively, and with low traffic impact if the issue is found in time. With the right information from timely inspections, repairs can be done for much less, sometimes with a 45x cost reduction [Langlie 2016].

Understanding the importance of culvert inspections, the Vermont Agency of Transportation (VTrans) adopted a policy requiring all culverts to be inspected every 5 years. This results in around 9,600 culverts needing to be inspected annually [Griffin 2019]. VTrans has 47,873 small culverts which cannot be inspected visually. 9,358 of those culverts are in critical, poor, or unknown condition and cross under a roadway [Griffin 2019].

A trained inspector can walk through and visually inspect large culverts, with diameters greater than 1.219 m (48 inches). Smaller culverts cannot be visually inspected and require an alternative method of inspection. One approach is to remotely control a small robotic vehicle through a culvert. The inspector can then use the video footage from the vehicle to determine the culvert status.

VTrans has access to two types of culvert inspection vehicles – a Crawler and a Hydraulic Inspection Vehicle Explorer (HIVE 1.0, previously denoted HIVE). Both vehicles are capable in many respects but have shortcomings that limit the efficient inspection of many small culverts.

The crawler is a commercially sourced vehicle. Figure 1.a shows the crawler, which tethers to a utility van with communications, power and video cables, Figure 1.b. The crawler is generally quite capable, but expensive, not able to inspect many culverts quickly, not able to inspect culverts in hard to access areas, and requires a team of 2 personnel, along with a specialized support van. The tether provides a long range of operation, but not long enough to access culverts with entry points far from the road. A traffic control plan with flaggers and signs may be necessary since the support van cannot always pull off the roadway. Additionally, the system is expensive, costing around $80,000 [Griffin 2019]. VTrans has access to only one crawler which must be booked ahead of time before use. Acquiring the crawler for an inspection is a slow process, limits rapid deployment and cannot not be relied on to inspect almost 10,000 small culverts annually.

Due to the cost and availability of the crawler, alternative affordable inspection vehicles were pursued. VTrans also uses a fleet of about a dozen in house-built HIVE 1.0 culvert inspection vehicles, Figure 2. The HIVE 1.0 is a modified version of a vehicle developed by MnDOT [Coughlin 2016] [Griffin 2019]. The HIVE 1.0 is lightweight, low-cost, and can be operated by a single inspector without a specialized support vehicle. The system incorporates a Sony Action Cam mounted with servo motors on a Traxxas remote control car. The video signal transmission is wireless, and the vehicle does not require a utility van for operation. A single person can carry all equipment to the culvert and perform the inspection wirelessly. Additionally, the vehicle only costs around $1,500 to build. While smaller and far less expensive than the crawler, the HIVE 1.0 has a short operation range and maneuverability limitations. A chronic issue is the video transmission range. The video signal can be lost when driving through long culverts or when operating through a drop inlet (DI). Specifically, the 2.4 GHz Sony Action Camera struggles to transmit video more than 40 feet (12.2 m) through an 18-inch (0.46 m) culvert. A recent survey of the state-of-the-art of culvert inspection technologies also identified the short telemetry range as a significant constraint on the performance and utility of radio-controlled (RC) robotic vehicles [Lehmann 2020]. The HIVE 1.0 can also become stuck or unable to maneuver through obstacles in culverts.

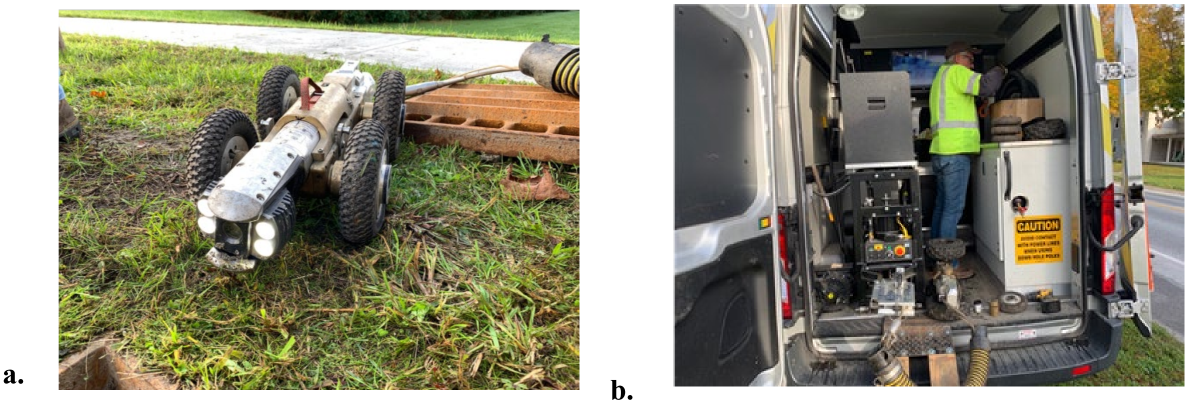

a.
b.

Figure 1. VTrans crawler culvert inspection vehicle: a. Crawler vehicle and b. Support vehicle with tether.

Figure 2 HIVE 1.0 used by VTrans with articulated Sony Action Cam video camera mounted on two servo motors

1.2 Project Goal and Objectives

The *primary goal of this project* is to produce a working prototype of an alternative culvert inspection vehicle design that improves upon the HIVE 1.0 to enable VTrans to inspect their large quantity of small culverts more affordably and effectively.

The primary objectives of this project are:

1. Objective 1 – *Clarification of design requirements* – The requirements for the robot are specific at this point with improved mobility and telemetry and need to be confirmed with detailed specifications as the project initiates and proceeds.
2. Objective 2 – *Identify test sites* – Multiple test sites will be identified, both those with easy access from the UVM campus and those with important or challenging features elsewhere in Vermont.
3. Objective 3 – *Design, build and field test prototype robot* – The robot will be built as an improvement following the original HIVE 1.0, keeping the same design philosophy of low-cost and simplicity balanced against performance. Field tests will confirm performance and guide design improvements.
4. Objective 4 – *Change and improve robot based on field test results* – The initial prototype robot will be improved based on how it performs in the field tests in culverts near to UVM.
5. Objective 5 – *Fabricate and deliver functional robot* – A functional robot will be built, verified for performance and delivered to VTrans maintenance personnel for assessment. Modifications will be made as needed based on feedback.
6. Objective 6 – *Technology transfer, benefit quantification, and guidelines for implementation* – Information needed to fabricate and use the HIVE 2.0 robot will be provided. Benefits will be quantified through feedback from VTrans personnel. Guidelines for implementation will be included as an appendix to the final report.

1.3 Methodology and Tasks

This project was a collaborative effort between VTrans maintenance personnel with experience using the HIVE 1.0 for small diameter culvert inspections and researchers from the

University of Vermont College of Engineering and Mathematical Sciences to design a HIVE 2.0 robot to improve its sensing performance and functionality. The development and design focused on several aspects: 1) Improving the wireless communication reliability to extend the range of transmission, largely through identifying the available frequency bands with the best performance. 2) Mechanical design to improve HIVE 2.0 maneuverability, primarily through the adoption of a caterpillar or tank tread design 3). Attachment of lightweight wire to help retrieve the HIVE 2.0 if it gets stuck and to help with counting distance traveled. 4) To enable the HIVE 2.0 to inspect pipes in closed systems between DIs, with a mechanical structure that can lower and retrieve the robot and maintain communication between the robot and the operator.

The primary tasks to be undertaken in this project are:

1. Task 1 – *Clarification of design requirements* – Details concerning the design requirements for the HIVE 2.0 will be clarified at the initiation of the project and modified as necessary with consultation with the Technical Advisory Committee.
2. Task 2 – *Identify test sites* - Multiple test sites will be identified. The first set will be culverts with easy access from the UVM campus. These will be used for prototype robot testing and development. The second set will be other culverts, particularly those with important or challenging features elsewhere in Vermont. Identification of the test sites and means of access will involve consultation with VTrans personnel.
3. Task 3 – *Design robot* - The robot will be built as an improvement following the original HIVE 1.0, keeping the same design philosophy of low-cost and simplicity balanced against performance. Two principal design upgrades for the HIVE 2.0 are improved mobility and increased wireless telemetry distance.
4. Task 4 – *Build prototype robot* – Prototype robot will be built following design developed in Task 3. Assembly, machining, and printing of custom 3D parts will be performed at UVM.
5. Task 5 – *Field test of prototype robot* – The initial testing of the robot will be in the laboratory. Next, field tests will confirm performance and guide design improvements. These field tests

will occur in culverts with locations and access convenient to the UVM campus.

6. Task 6 – *Change and improve robot based on field test* – The initial field tests will identify needed improvements and performance limitation in the prototype HIVE 2.0. Redesign and improvement of the HIVE 2.0 will be implemented as needed.
7. Task 7 – *Fabricate and deliver functional robot* – Based on field tests and improvement of the prototype HIVE 2.0, a functional robot will be fabricated and delivered to VTrans maintenance personnel for performance testing and verification.
8. Task 8 – *Documentation and reporting* – This task includes technology transfer, benefit quantification, and delivery of guidelines for implementation. Information needed to fabricate and use the HIVE 2.0 robot will be provided. Guidelines for implementation will be included as an appendix to the final report.

1.4 Strategic Alignment

VTrans owns 47,873 small culverts. This research product has the potential to greatly improve the efficiency and accuracy of culvert inspections and bring down inspection cost. Should a new robot be successfully designed and improved, it can be adopted by other transportation agencies to perform infrastructure inspection at places that not easily accessible by human inspectors. The benefits can be quantified by assessing the improvement in speed and quality of culvert inspections, along with the reduced costs.

This project aligns with VTrans Strategic Goals 1, 2, and 5 as listed in https://vtrans.vermont.gov/about/mission-and-vision

Goal 1: *Provide a safe and resilient transportation system that supports the Vermont economy.*

- *No unplanned road closures or restrictions due to conditions within VTrans' control* - Culverts that fail can lead to subsurface erosion, water ponding, slope instabilities and sinkholes – all of which can lead to unexpected road closures and expensive emergency repairs. The HIVE 2.0 robot will help to better maintain culverts under highways and roadways. The low cost and relative expendability of the HIVE 2.0 means that a fleet can be readily deployed with VTrans maintenance crews throughout the state in an effective manner not practical with more expensive alternatives.

- *Increase the resilience of the transportation network to floods and other extreme weather and events* – Culverts play a major role in flood control and mitigation. Failed or underperforming culverts can exacerbate flooding and flooding-related damage. Maintenance of culverts prior to extreme flooding events is an effective tool for increasing resilience. The HIVE 2.0 robot will be a useful tool in assessing and planning culvert maintenance and post-flood assessment activities.

Goal 2: *Preserve, maintain, and operate the transportation system in a cost effective and environmentally responsible manner.*

- *Maintain pavement, structures, and other transportation system assets in a state of good repair* – The HIVE 2.0 robot will be low-cost tool assisting maintenance crews with culverts.
- *Implement an Asset Management System and integrate it with Planning and Programming* – The position-registered image data from the HIVE 2.0 will provide data for use in asset management, planning and programming.
- *Minimize the environmental impacts of the transportation system* – Culverts are key assets in managing storm water runoff. Well maintained culverts improve the performance and predictability of stormwater systems.

Goal 5: *Develop a workforce to meet the strategic needs of the Agency.*

- *Recruit excellent, qualified and diverse employees* – The use modern technologies, such as robots, will prove attractive to potential employees.
- *Retain and develop excellent and diverse employees* – The integration of robotic and digital asset management systems for maintenance will increase the skill levels of

employees, and reduce some the drudgery and dangerous work

1.5 Implementation Plan

The implementation plan includes:

- The product expected from the research is the design and delivery of a functional HIVE 2.0 robotic inspector for culverts that provides an improved low-cost inspection tool for culverts.
- The stakeholders or intended audience that will most likely be impacted by the research results are VTrans maintenance personnel that inspect and maintain culverts
- The HIVE 2.0 robot technology can be implemented first on a local scale with pilot tests by VTrans maintenance personnel and if successful implemented on a statewide basis with the assembly of a fleet of HIVE 2.0 robots.
- Potential impediments to implementation include the HIVE 2.0 not meeting the technical requirements and it possibly not having a suitable human interface for convenience of use
- Activities necessary for successful implementation include fabrication, testing and verification as described in this proposal and pilot testing by VTrans maintenance personnel.

2. HIVE 1.0 AND 2.0 REQUIREMENTS, SPECIFICATIONS AND PERFORMANCE

2.1 Overview

This chapter describes the background of this project with regards to the HIVE 1.0 design, use and performance limitations, followed by the formulation of a list of performance specifications for a HIVE 2.0. Table 2 lists the performance specifications for the HIVE 2.0, and the ability of the original HIVE 1.0 and new HIVE 2.0 to meet these specifications.

2.2 HIVE 1.0 Background

The Hydraulic Inspection Vehicle Explorer (HIVE 1.0) was developed by the Minnesota Department of Transportation to provide an affordable method of inspecting small culverts [Youngblood 2017]. VTrans subsequently adopted the design with minor modifications in 2018 [Griffin 2019]. VTrans presently has 12 HIVE 1.0s in their fleet. The HIVE 1.0 incorporates a SONY action camera mounted with servo motors on a Traxxas remote control car, Figure 3. The video signal is transmission is wireless and the vehicle does not require a utility van for operation. A single person can carry all equipment to the culvert and perform the inspection remotely through a wireless interface. The HIVE 1.0 costs around $1,500 to build. Table 1 lists the parts used in the MnDOT HIVE 1.0 along with 2019 prices.

The HIVE 1.0 can perform culvert inspections quickly and affordably. However, this design has limitations:

- The HIVE 1.0 moves very fast. Operating it with minimal experience and proficiency is a challenge.
- It does not perform well in mud. If a culvert is heavily sedimented it will not be able to go far. More than two inches of muck led to limited success.
- Water depths exceeding 102 mm (4 inch) will probably hamper the movement. The HIVE 1.0 can be fully submerged and still operate, but it will not travel far underwater due to loss of the radio signal.

- The HIVE has trouble with debris (sticks, leaf litter, trash). In pipes where there is a lot of debris, it is difficult to get the HIVE 1.0 around all the debris. There is a risk of getting it hung up and stuck. Once out of 141 deployments the operator struggled to get it free after it was stuck.
- The HIVE 1.0 does not work well in culverts where the bottom is decomposed, especially corroded corrugated steel where it tends to get hooked and then stuck on the exposed corrugations.
- Sloped pipes: The HIVE 1.0 will go up them (or down them) but it does not have brakes. If you drive up, it is difficult to get it back down because it will come zipping back.
- When the HIVE 1.0 is deep in a long pipe, the wireless communication with the external operator/computer can get disconnected, making the real time monitoring not possible. Small diameter concrete pipes are the most difficult cases. Similarly, the video signal can be lost when operating through a DI.

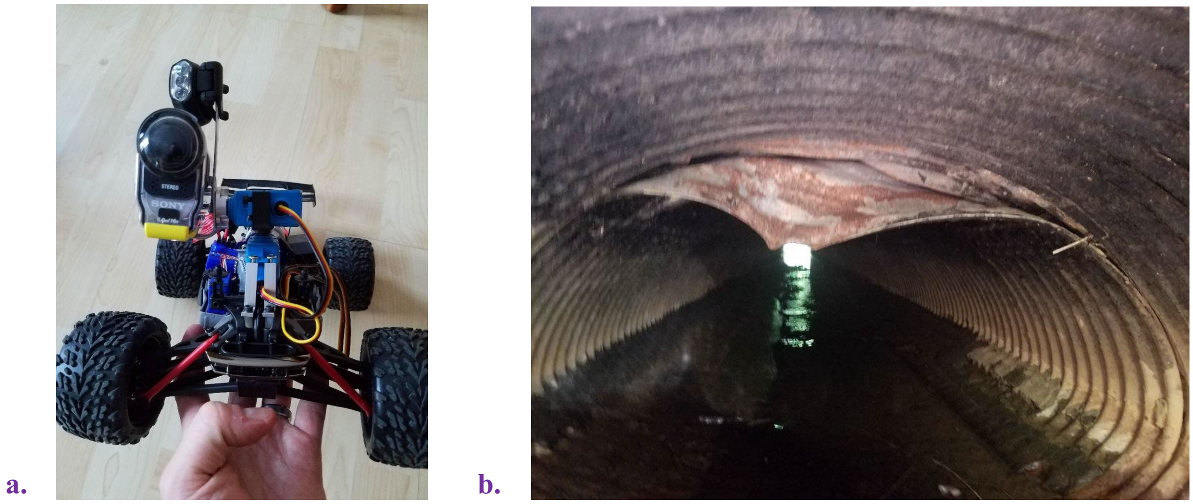


Figure 3 a. HIVE 1.0 robot built by VTrans, b. Corrugated steel culvert [Griffin 2019]

Table 1 Parts List with 2019 prices for MnDOT HIVE 1.0, adapted from [Coughlin 2016]

Description	Item #	Brand or Vendor	Cost ($)
HD Action Camera	HDR-AS100V	Sony	299
Tablet	Galaxy Tab A	Samsung	150
Tablet Case	Samsung Gal. 9.7	AVAWO/Amazon	17
1/16 E-Revo (waterproof remote control car)	TRA71054	Traxxas	200
Transmitter	FUTK4200	Futuba	117
Receiver (comes with transmitter)	R2004GF	Futuba	59
Camera gimbal servo (X2)	HS646WP	Hitec	63
Traxxas Battery Charger	TRA2972	Traxxas	100
Front mount for lower gimbal servo	210007	www.servocity.com	7
Rear mount for lower gimbal servo custom			
Lower servo horn for upper servo mount	FUTM2110	Futaba	8
Upper servo mounts	1779	Team Associated	14
Camera mount to upper servo horn custom			
Upper servo horn (for Hitec Servo)	525130	www.servocity.com	5
Extra vehicle battery (X2)	TRA2925X	Traxxas	40
Parallel Wiring Harness	TRA3064X	Traxxas	8
Misc Screws & Washers as needed			
Lighting (3-LED Swivel Cap Light)	60931	Mills Fleet Farm	14
Lighting (3 LED Cap Lamp)	Y0949	DHGate.com	15
RecoveryCable 1/32in.	33RG76	Grainger	51
Cable Sleeve and Thimble kit	1DKJ6	Grainger	3
Recovery Cable Spool	162532	Northern Tool & Equipment	27
HIVE Case (Plano Storage Trunk)	1619-00	Menards	47
Total			$1,244

A series of communications with VTrans personnel, including the Technical Advisory Committee (TAC) for this project identified a list of key requirements and engineering specifications for the HIVE. Table 2 lists the requirements, along with whether these were met with the existing HIVE 1.0. The specifications highlighted in green, red, and orange show what the original HIVE passed, failed, and moderately passed, respectively.

Table 2 HIVE 1.0 and 2.0 Requirements, Specifications and Performance

No.	VTrans Requirements	Engineering Specifications	HIVE 1.0	HIVE 2.0
1	Capable of fitting inside small culverts	Maximum vehicle height of 8 inch (203 mm)	Meets specification	Meets specification
		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
		Vehicle shall travel over a step change in height of at least 2 inches (5.080 cm)	Meets specification	Meets specification
		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 inches (16.240 cm)	Does not meet specification	Meets specification
8	Capable of functioning in water	Vehicle shall drive through 4 inches (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+/- l'	Moderately meets specification	Meets specification

		(305 mm) in culvert at all times		
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
		All system components shall weigh no more than 30 lbs (0.454 kg) collectively	Meets specification	Meets specification
		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

The main requirement not met by the HIVE 1.0 was the ability to view video signals at least 30.5 m (100 feet) into an 0.457 m (18 inch) culvert. Additionally, the emphasis was the importance of being able to operate the vehicle through a DI. These requirements guided the decisions made during the design process for the HIVE 2.0. Quantifiable benefits of the HIVE 2.0 design over the HIVE 1.0 are the ability to meet the specifications: 3. Footage available deep into small culverts; 4. Footage available through drop inlets; 7. Capable of crossing separation gap in pipes; 9. Capable of stopping from rolling down hills; and 11. User capable of knowing vehicle's location.

3. HIVE 2.0 DESIGN AND PROTOTYPE TESTING

The specifications listed in Table 2 drove the selection of design alternates and concepts for the HIVE 2.0. Details on designs, rationale, and prototype testing follow. Appendix A lists the required parts and pricing for the final design HIVE 2.0.

3.1 Chassis Selection and Design

A design priority is to meet enhanced maneuverability requirements. From Table 2 these include:

Specification 1 – Capable of fitting inside small culverts; Maximum vehicle height of 230 mm (8 inch), and Maximum vehicle width of 229 mm (9 inch)

Specification 6 – Capable of traversing through culverts; Vehicle shall travel through sediment sludge, Vehicle shall travel over a step change in height of at least 50.8 mm (2 inch), and Vehicle shall travel up slope of at least 20-degrees.

Specification 7 – Capable of crossing separation gap in pipes; Vehicle shall span a gap of at least 162 mm (6 inch).

Specification 8 – Capable of functioning in water; Vehicle shall drive through 102 mm (4 inch) of water.

Specification 9 – Capable of stopping from rolling down hills; Vehicle shall remain still on 20 degree slope.

Specification 14 – Affordable; One system shall cost no more than $2,500.

The cost constraints of Specification 14 limit the available vehicle chassis options to commercially available mass-produced variants. The majority of the available vehicle chasses are hobby remote control (RC) vehicles. These vehicles tend to be rugged, have mechanical drive trains and suspensions with components that mimic full size vehicles, have remote wireless control telemetry, and move at reasonable speeds. The cost constraint of Specification 14 was not a significant constraint otherwise. The cost for the parts for the final design is $1,175 in August 2020 pricing. This does not include labor of about 8 hours to assemble. The ability to meet the cost specification with relative ease then directed the design decisions to an emphasis on meeting the performance and usability specifications, as indicated in Specifications 1 to 13.

The original HIVE 1.0 had a free-wheeling drive train that allowed for the car to move with minimal force while the drive motor was not engaged. The HIVE 1.0 rolled downhill easily and was not capable of meeting Specification 9.

The Minnesota Department of Transportation implemented a 3D printed wheel modification for the HIVE 1.0. These larger wheels helped the HIVE 1.0 traverse through sludge, over small gaps and over obstacles. However, the vehicle was still unable to remain stationary on a slope and the large wheels made the vehicle too large to fit in some culverts. Also, the wheels were still susceptible to getting stuck in separation gaps.

An alternative 4-wheel drive vehicle is the Losi Night Crawler 2.0, Figure 4 [Losi]. This vehicle is larger than the HIVE 1.0 chassis. It has worm-gear differentials that are self-braking and satisfy Specification 9. Concerns about being too big and the ability to span 162 mm (6 inch) gaps led to the non-selection of Night Crawler 2.0 for the HIVE 2.0.

Figure 4 Losi Night Crawler 2.0 with 4-wheel drive and worm-gear differentials that provide self-braking [Losi 2020]

To avoid issues associated with wheels, consideration turned to a vehicle with treads. Using the chassis of a RC tank enables the vehicle to cross separation gaps and remain still on slopes.

Additionally, many RC tanks include a rotating turret which could be used for rotating the azimuth angle of a camera. There are many RC tanks available in 1/16 and 1/20 scales. The 1/20 scale tanks would likely have issues climbing over larger obstacles due to their smaller size. Most of the 1/16 scale tanks are slightly larger than the VTrans size requirements. However, the 1/16 Sherman M4A3 remote control tank shown in Figure 5 is an appropriate size. Using this RC tank chassis solves several issues that make the vehicle more maneuverable, simpler, and cheaper. The tracks of the tank allow for the vehicle to clear separation gaps up to 150 mm (6 inches). The tank is also able to remain stationary on slopes of at least 20 degrees.

This tank can come with an optional metal drive train for enhanced durability. The cost of this upgrade is less than $50 (2020 prices). The tank used in this report used a plastic drive train, which performed without any issues, but was not subjected to long term loading. The durability of the metal drive train and potential issues of corrosion have not been verified.

Figure 5 1/16 scale Sherman M4A3 remote control tank

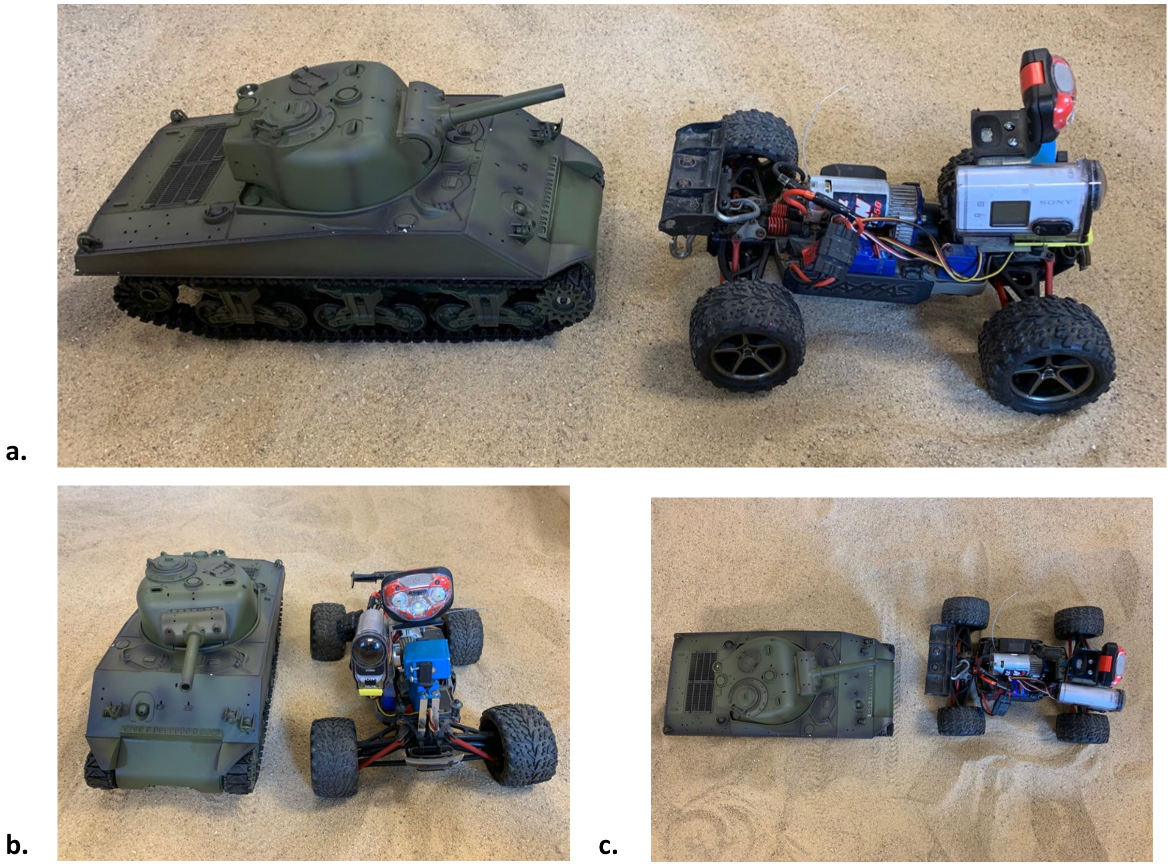


Figure 6 HIVE 1.0 v. HIVE 2.0: a. Side view, b. Front view, c. Top view

3.2 Tank Chassis Waterproofing

A key mobility requirement is Specification 8 which requires that the HIVE 2.0 be able to drive through 102 mm (4 inch) of water. This requirement imposes two separate constraints on the HIVE 2.0. The first is that the tank should survive immersion and even complete submersion in water. The second is that the tank should be able to maneuver in standing and running water.

The primary issue with surviving water immersion is to protect the electronics. Water can cause shorts, open circuits, and corrosion. One method of protecting the internal electronics and critical components of the tank from water is to encase them in a watertight container. The tank chassis has a curved and faceted geometry that does not permit easy encasement, Figure 7. A further complication is that drivetrain components, e.g. shafts, and wires must penetrate the case for routine operation. These penetration points, while potentially sealable, are potential future leak points. Figure 8 shows an attempt at sealing the tank chassis with a fitted plastic bag. The bag worked well but was labor intensive to install, prevented further maintenance of components and had difficulty with sealing around a penetrating wire bundle.

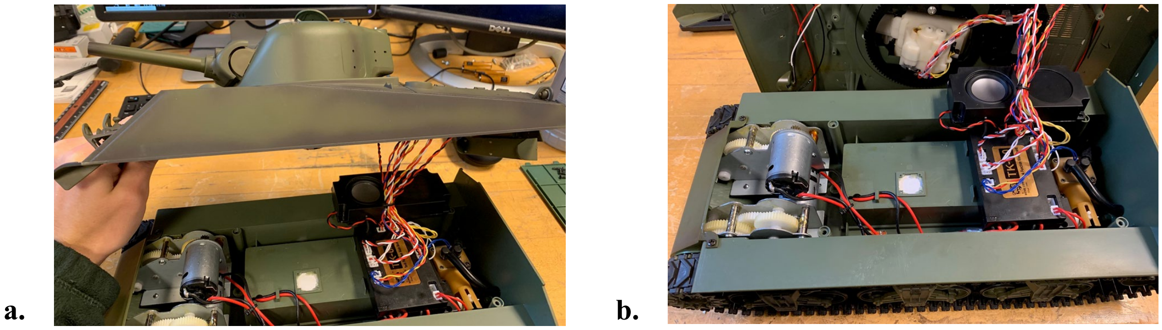


Figure 7 Internal components and geometry of HIVE 2.0 tank

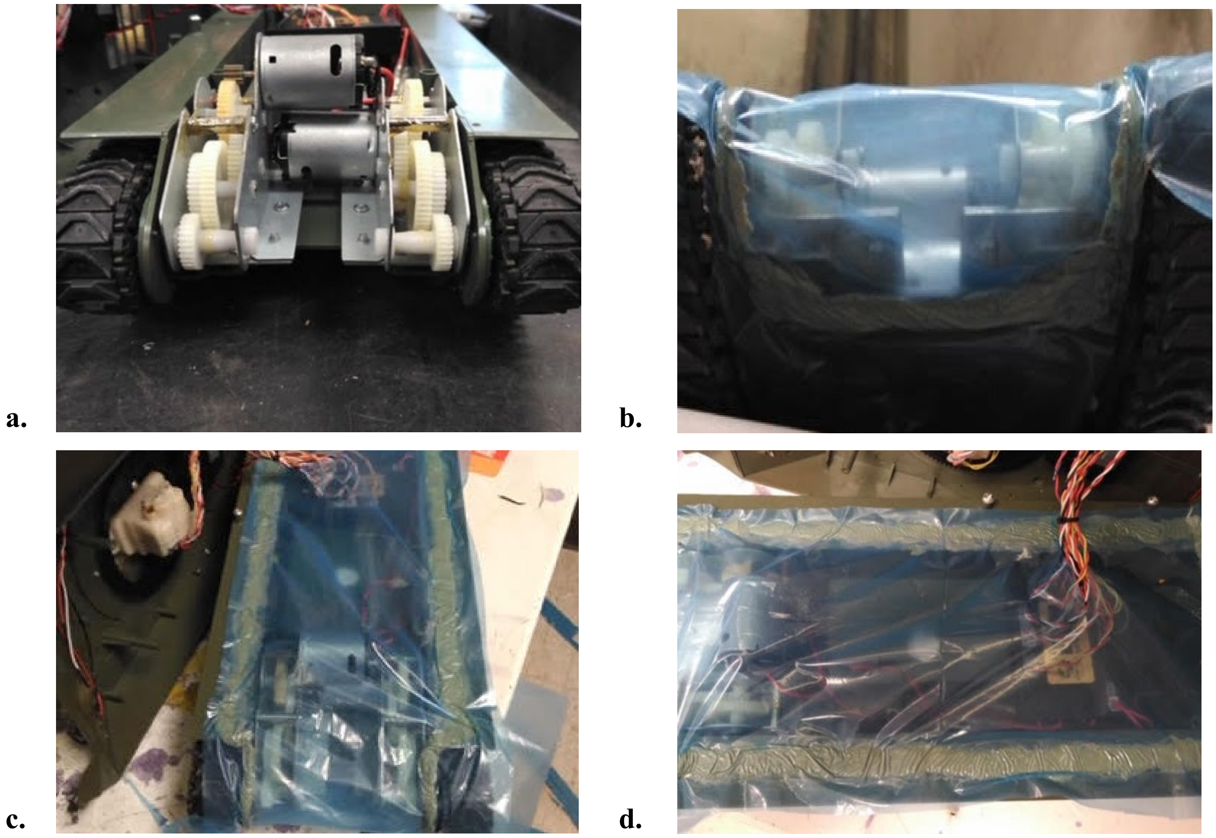


Figure 8 Attempt at waterproofing tank by sealing drivetrain and electronics of HIVE 2.0 tank in plastic bag: a. Internal motor and drive gears, b. Bottom view of motor and drive gears in plastic, c. Bag encases internal components with gasket seal on perimeter, and d. Wires penetrate bag and form difficult to seal potential leak zone.

Spray-on waterproofing compounds are an alternative to encasement. The application of spray coating can waterproof the internal components of a HIVE 2.0 in a simple process. A series of tests evaluated the viability of these compounds. The first test coated a small DC motor in a polyurethane sealant, and then submersed a running motor in water, Figure 9. The coated motor continued to operate normally while submersed.

Figure 9 Waterproof coating submersion test: a. Polyurethane spray coating, and b. Submersion test of coated running DC electric motor

The success with spray-on coating for waterproofing motivated the development of a potentially more robust two-layer system. The bottom layer is a spray-on polyurethane. The top layer is a proprietary mix of mineral spirits, liquified petroleum gases and crystalline silica with the trade name CorrosionX Heavy Duty. Applying this double layer of sealing to the inside components of the HIVE 2.0 tank was straightforward but was messy and required proper ventilation. The result was a waterproofed vehicle. The first test was an immersion test which submerged the tank in a water filled tub. The tank was able to operate fully submerged. This included receiving and acting on short range RC telemetry signals, Figure 10. Next the tank underwent water tolerance testing in a nearby stream, Figure 11. The HIVE 2.0 tank withstood the water without any adverse effects.

Figure 10 Submersion test of HIVE 2.0 tank that successfully operated under water with wireless remote-control telemetry

Figure 11 Waterproofed HIVE 2.0 tested for water tolerance in a stream

The stream tests did identify an unanticipated issue – flowing water exerts lift and drag forces on the low-profile tank body, Figure 12. The forces can lift and push the tank off the intended direction of movement. The HIVE 1.0 car tends to not experience this problem because the elevation of the 4-wheel suspension lifts the body further up and out of the flowing water and presents a more streamlined cross section. After consideration of various options, the choice was to modify the geometric form of the tank body with a set of cutouts and holes that allow for water to flow freely through the body, Figure 13 and Figure 14.

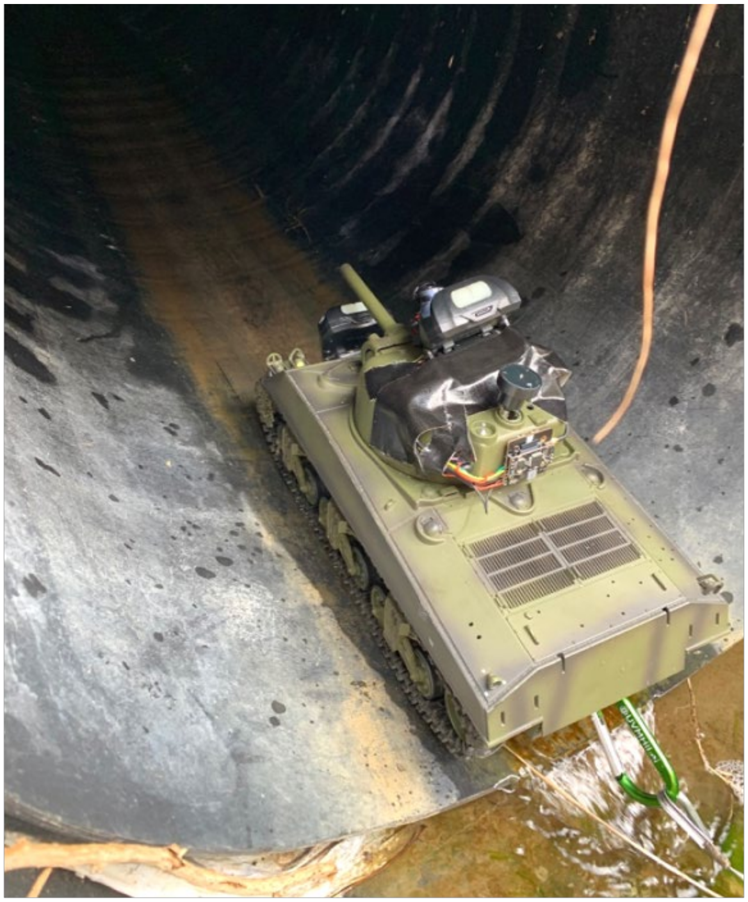


Figure 12 Flowing water in a culvert can be a mobility issue for unmodified HIVE 2.0 tank

a.

b.

Figure 13 Holes drilled into HIVE 2.0 tank to allow internal flow of water and reduce drag: a. Side undercarriage, b. Bottom

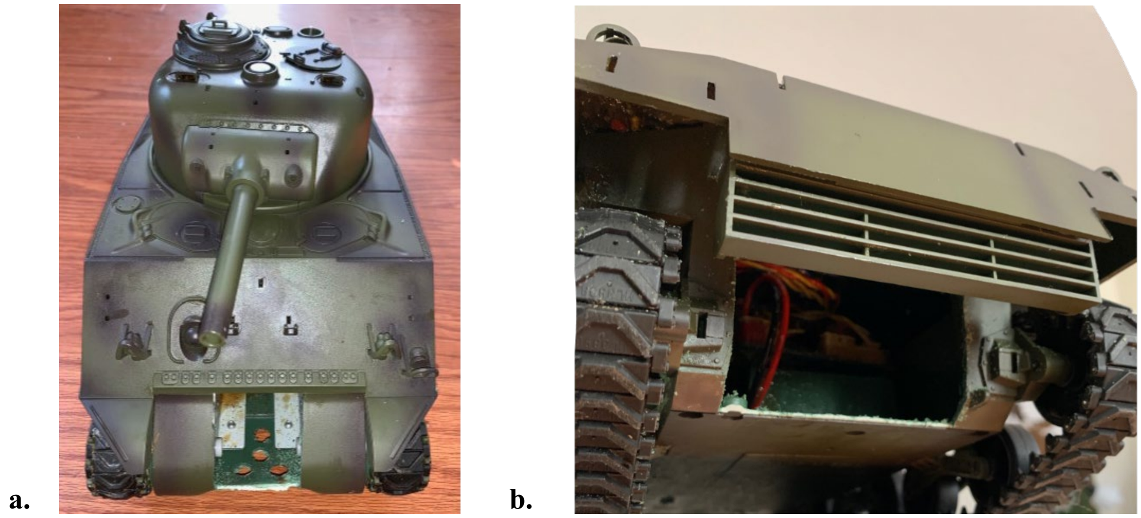


Figure 14 Cutouts in HIVE 2.0 tank body to allow free flow of water: a. Front with cutout, and b. Back with cutout

Subsequent testing found these holes and cutouts to be effective in reducing the lift and drag on the HIVE 2.0 tanks by running water, Figure 15.

Figure 15 Stream testing confirms viability of cutouts and holes in reducing lift and drag of flowing water on HIVE 2.0 tank

3.3 HIVE 2.0 Tank Chassis Mobility Testing

A mobility test of the HIVE 2.0 chassis examined the ability of the tank to drive through a culvert with a 102 to 152 mm (4 to 6 inch) separation gap that previously caused the HIVE 1.0 car to become stuck. Instrumenting the waterproofed unmodified tank with a taped-on light and 5.8 GHz video telemetry system assisted in driving the vehicle through the culvert, Figure 16. The test location was a Culvert 64099 under U.S. Route 7 in Charlotte, VT, Figure 17. The culvert had a galvanized steel lining, 762 mm (30 inch) diameter and length of 51.2 m (168 feet). The results of the test were that the vehicle could maneuver under RC telemetry down the entire length of the culvert. The unmodified tank chassis traversed 25 to 50 mm (1 to 2 inch) of water and cleared the 102 to 152 mm (4 to 6 inch) separation gap.

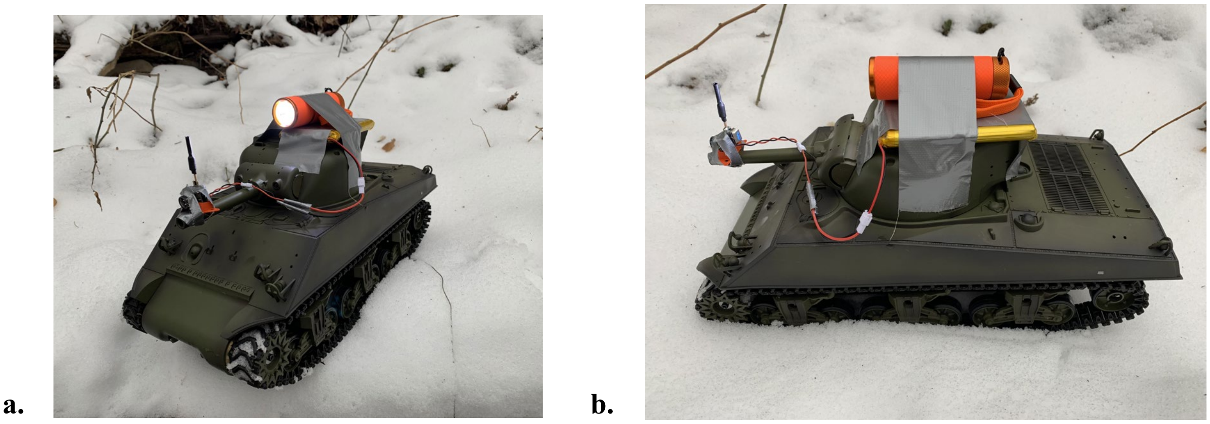


Figure 16 Unmodified HIVE 2.0 with taped-on light and 5.8 GHz video telemetry system

Figure 17 Mobility testing of HIVE 2.0 Tank in metal lined culvert with flowing water and separation gap in Culvert 64099 under U.S. Route 7 in Charlotte, VT

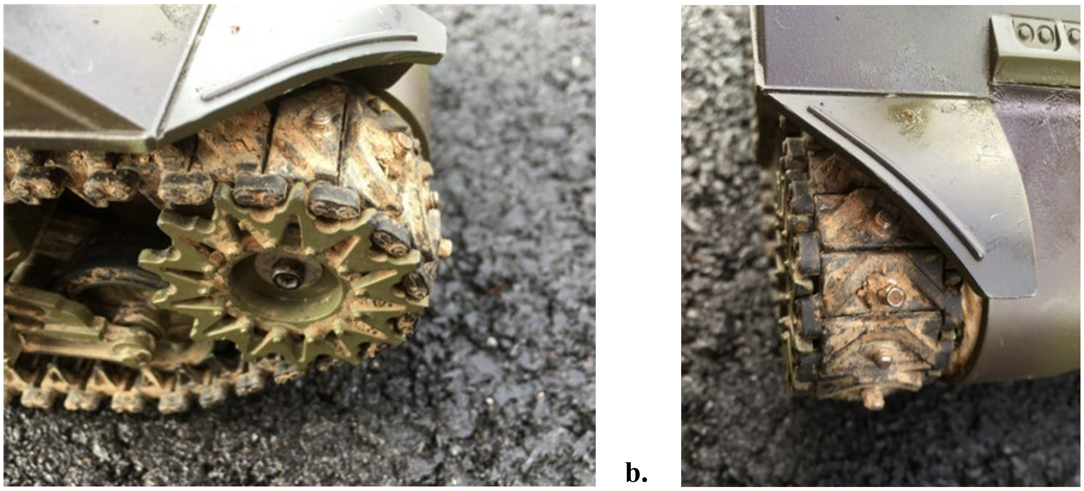
3.4 Additional Chassis Modifications - Tank Turret, Gun Barrel, Lighting and Traction Studs

The tank has a built-in turret with an azimuthal rotation capability of 360-degrees about the vertical axis. This built-in functionality replaces servo motors used on the HIVE 1.0. The tank has a Sherman Tank body form characterized by a vertically protruding turret. The turret acts as a shield to protect the cameras from damage. Attached to the turret is a gun mount that can raise and lower the barrel through an angle of 15 degrees.

An optimized camera configuration used two cameras inserted into a modified turret. The modifications included removing the gun barrel, cutting openings for apertures for the cameras and using jogging headlamps for lighting. The telemetry configuration uses a circular antenna and places the telemetry system on an isolated battery power supply. Figure 18 shows a prototype assembled HIVE 2.0.

Figure 18 Modified HIVE 2.0 showing water passage cutout in front, modified turret with forward looking and elevated cameras, jogging headlamp light and circular antenna.

Mobility testing identified tank tread slippage when maneuvering over debris and wet objects to also be a potential. The addition of studs in the form of short bolts (4-40 1/8 inch) glued to the treads improved the overall traction,



a. b.

Figure 19 Short bolts glued to tank treads improve traction, especially when climbing over debris and slippery surfaces.

3.5 Retrieval Cable

A thin metal cable attached to the HIVE 2.0 provides emergency retrieval capabilities. The cable also enables tracking the distance the tank has traveled by connecting the cable to a spool with a magnetic revolution counter to track this distance. Figure 17 shows the HIVE 2.0 entering a 0.762 m (30 inch) culvert equipped with a 5.8 GHz telemetry system and connected to a cable spool.

Figure 20 Retrieval wire spool with magnetic revolution counter

3.6 Telemetry Analysis

The HIVE 1.0 experienced difficulties in transmitting wirelessly the video signal more than 12.2 m (40 feet) into a small 0.457 m (18 inch) diameter culvert. Methods for extending the range of wireless video transmission through a culvert are not inherently obvious. There is minimal information published on this specific topic. A large amount of work has been done to characterize wave propagation in waveguides. A culvert is a mixture of the line-of-sight and tightly contained geometries. Since a culvert provides line-of-sight access, one could argue that higher frequencies around 5.8 GHz would operate best. However, since the culvert is tightly contained, high frequencies may become distorted due to the increased levels of refraction so that lower frequencies from 1.2 to 2.4 GHz would transmit the video best. Some insight can be gained with analysis that considers a culvert to be a large electromagnetic waveguide.

Waveguides are elongated cavity structures which can guide waves to transmit power and communication signals with less losses than transmission cables. When propagating in open space, the power of an electromagnetic wave decreases at a rate inversely proportional to the square of the distance. However, when a waveguide guides a wave in a single dimension with ideal conditions due to the reflectively at the walls the power loss is zero. Figure 21 shows the geometry of a rectangular waveguide with width a and height b and extending along the +z-direction. Many waveguides are curved in the x and/or y-directions. Curved waveguides work as well as straight ones, if the radius of curvature is significantly larger than the wavelength of the signal and the walls act as no-loss reflectors.

Analytic descriptions of the propagation of electromagnetic fields through waveguides use interactions of the electric field vector with components E_x, E_y and E_z; the magnetic field vector with components H_x, H_y and H_z; and the environment, such as the confining boundaries of a waveguide. In the case of the waveguide shown in Figure 21 the boundaries confine the fields to a rectangular region in the x and y directions, which allows waves to propagate only in the +z-direction. Three groups of electromagnetic waves are:

1. *Transverse electromagnetic* (TEM) waves: The electric and magnetic fields in the direction of propagation are zero, $E_z = H_z = 0$.
2. *Transverse electric* (TE) waves: The electric field in the direction of propagation is zero and the magnetic field is non-zero, $E_z = 0$ and $H_z \neq 0$.
3. *Transverse magnetic* (TM) waves: The magnetic field in the direction of propagation is zero and the electric field is non-zero, $H_z = 0$ and $E_z \neq 0$.

When transmitting a signal through a waveguide, the dimensions of the waveguide must correspond appropriately to the wavelength of the signal being transmitted. If the waveguide is not sized appropriately for the wavelength of the input signal, the signal may not propagate through the waveguide or be heavily distorted. For any waveguide, there is a minimum frequency of the signal that propagates through the waveguide. This frequency, known as the cutoff frequency, f_c, is the minimum frequency necessary for a TE or TM wave to propagate through a waveguide.

Determining the cutoff frequency is important when designing waveguides to ensure wave propagation.

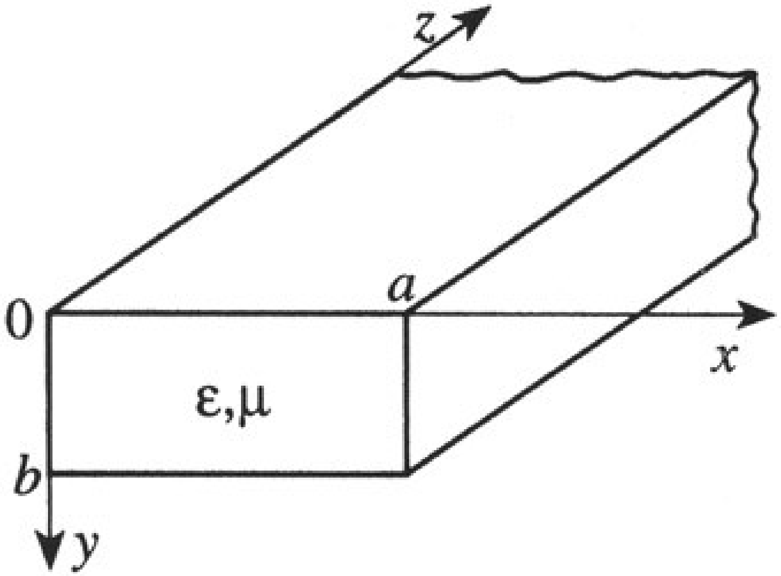


Figure 21 Rectangular waveguide coordinate system [Russer 2006]

TE and TM waves propagate in waveguides. The reflection constraint at the walls cause either the electric or magnetic field to propagate in the +z-direction. Figure 22 shows a TE wave in a rectangular waveguide. The solid lines represent the electric field, and the dashed lines represent the magnetic field. This shape corresponds to the definition of TE waves with the electric field lines being perpendicular to the z-axis, i.e. $E_z = 0$ and the magnetic field lines have some components in the z-direction, i.e. $H_z \neq 0$. TE and TM waves have different modes denoted as TE_{mn} and TM_{mn}. Where m is the number of half periods of the wave in the x-direction, and n is the number of half periods of the wave in the y-direction. Figure 22 shows the TE_{10} mode. The TE_{11} and TE_{20} modes appear in Figure 23.

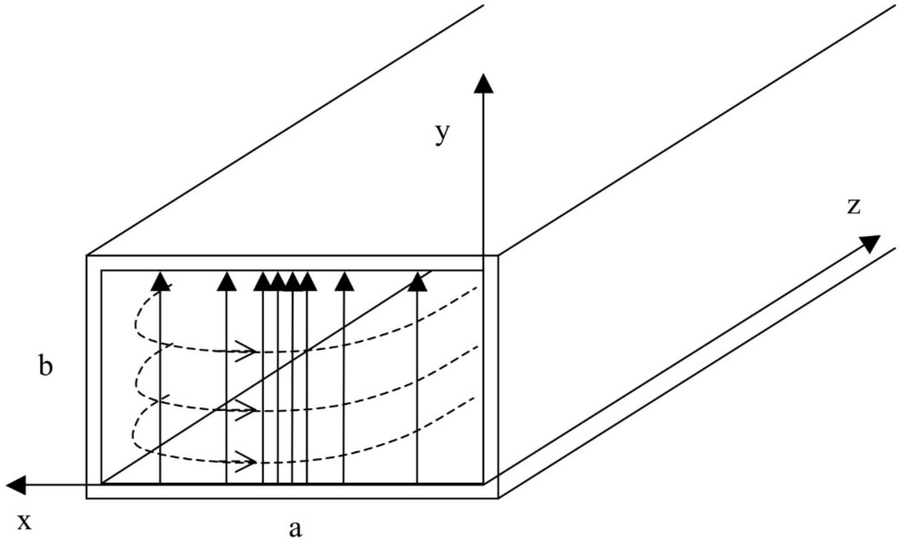


Figure 22 TE$_{10}$ mode in rectangular waveguide [Engan 2006]

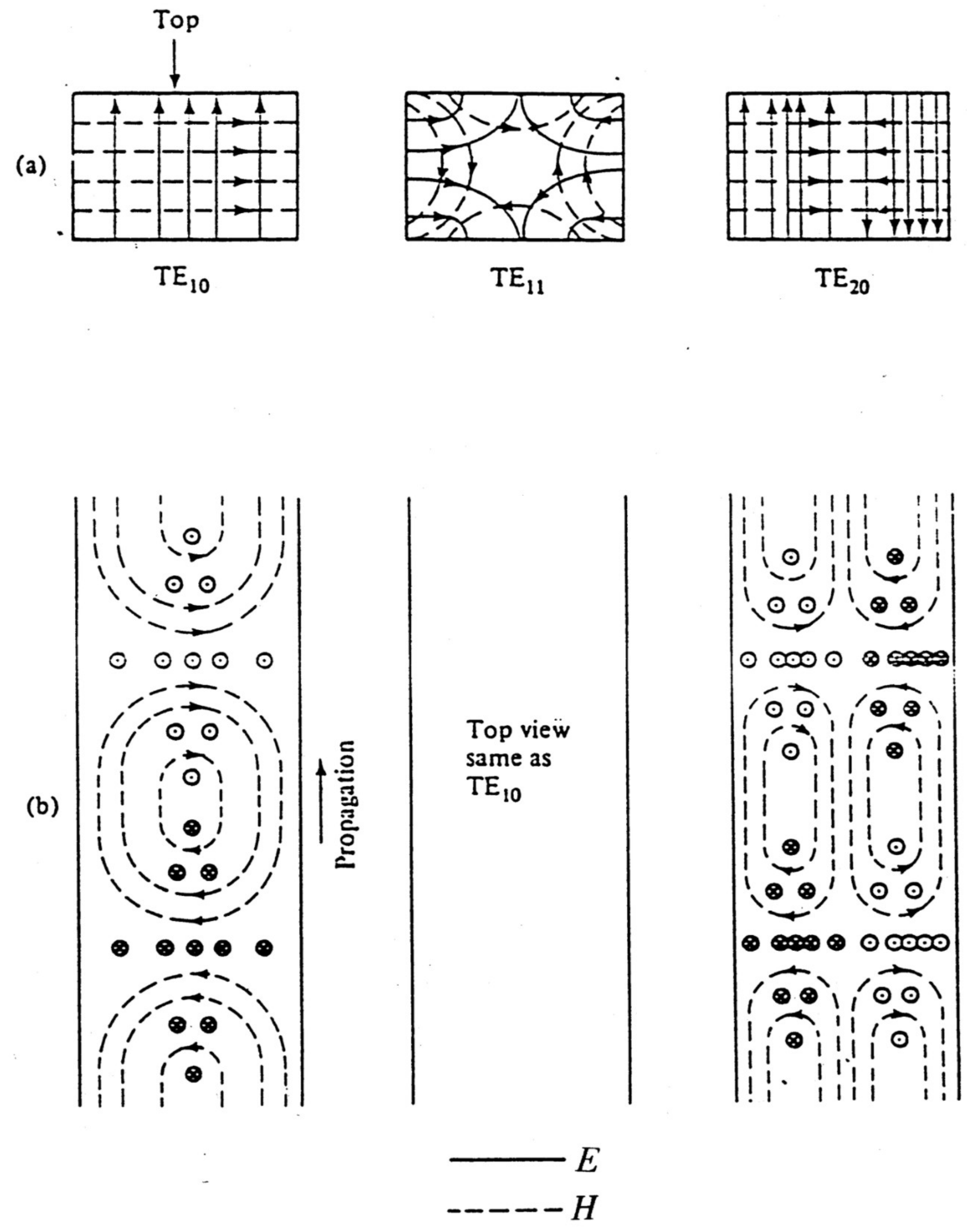


Figure 23 Higher order TE modes in rectangular waveguide [Engan 2006]

The mode of the TE or TM wave affects the cutoff frequency, $f_{c,mn}$, which is given as

$$f_{c,mn} = \frac{c_0}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \qquad (1)$$

and c_0 is the speed of light in a vacuum (approx. 3 x 10^8 m/s), and m and n correspond to the mode numbers. Modes with more half periods, seen as larger m and n values, have higher cutoff frequencies. A mode of m = n = 0 does not exist since this would require that neither the electric nor magnetic field propagate in the z-direction. The two modes with the lowest cutoff frequencies are either TE_{01} or TE_{10} for rectangular waveguides.

Waveguides with circular cross sections propagate waves with cylindrical symmetries. The cutoff frequency, $f_{c,\nu n}$ for a circular waveguide is given as

$$f_{c,\vartheta n} = \frac{p'_{\vartheta n} c_0}{2\pi a} \tag{2}$$

and $p'_{\vartheta n}$ is the nth zero of the first derivative of the Bessel function of the first kind of order ν, and a is the inner radius of the waveguide. The cutoff frequency for the dominant mode of a circular waveguide, TE_{11} is

$$f_{c,11} = \frac{p'_{11} c_0}{2\pi a} = \frac{1.8412 c_0}{2\pi a} \tag{3}$$

The cutoff frequency for the second mode, TE_{21}, is

$$f_{c,21} = \frac{p'_{21} c_0}{2\pi a} = \frac{3.0542 c_0}{2\pi a} \tag{4}$$

Table 3 lists the cutoff frequency for the dominant TE_{11} and second TE_{21} mode for two small culvert-sized circular waveguides. The waveguides have diameters of 0.457 m (18 inch) and 0.762 m (30 inch).

Table 3 Cutoff frequencies of circular waveguides used in example calculations

Waveguide Characteristics				
Number	Type	Diameter (m)	$f_{c,11}$ for TE_{11}	$f_{c,21}$ for TE_{21}
1	Circular	0.457	385 MHz	638 MHz
2	Circular	0.762	231 MHz	383 MHz

The above analysis indicates that there is a minimum input frequency necessary for a wave to travel through a waveguide. The mode with the lowest cutoff frequency is considered the dominant mode. The single mode range is the frequency range between the dominant mode and second lowest mode. Waves travel with minimal distortion through a waveguide when the frequencies fall within the single mode range. The formulas used in this analysis suggests that frequencies around 500 MHz are ideal for 0.457 m (18 inch) culverts and 300 MHz for 0.762 m (30 inch) culverts. 200 MHz is too low of a frequency to be capable of video transmission. The readily available frequency bands for HIVE radio control and video telemetry are 900 MHz and higher.

The above waveguide analysis assumes that the walls of the culvert are perfectly conductive. This leads to the mathematical boundary conditions of perfect reflection in the walls, which then drives many of the classical waveguide results. Two primary results are: 1. Waves with frequencies above the cutoff frequency propagate along the waveguide without any loss of energy or signal strength, Figure 24 and Figure 25; and 2. The waveguide can be curved without affecting the propagation of waves, as long as the radius of curvature is several times longer than the wavelength, Figure 26. Metal walls on a culvert can be a reasonable approximation to perfectly conductive and reflective walls, but the losses will attenuate the strength of the signals.

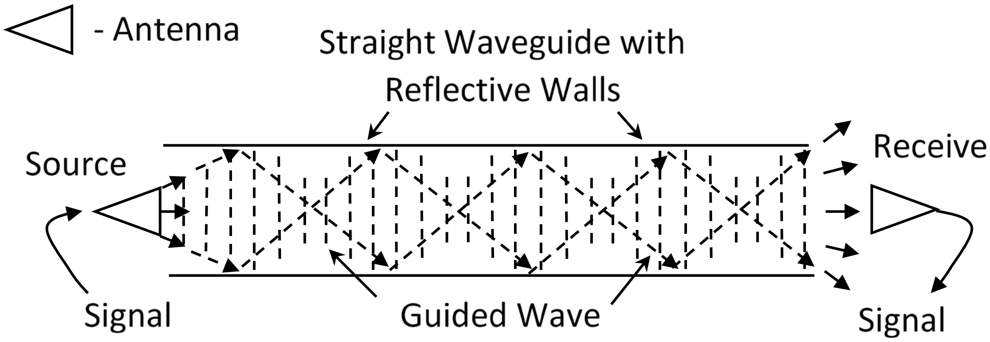


Figure 24 Waveguide with reflective walls transmits waves with frequencies above the cutoff frequency long distances without losses

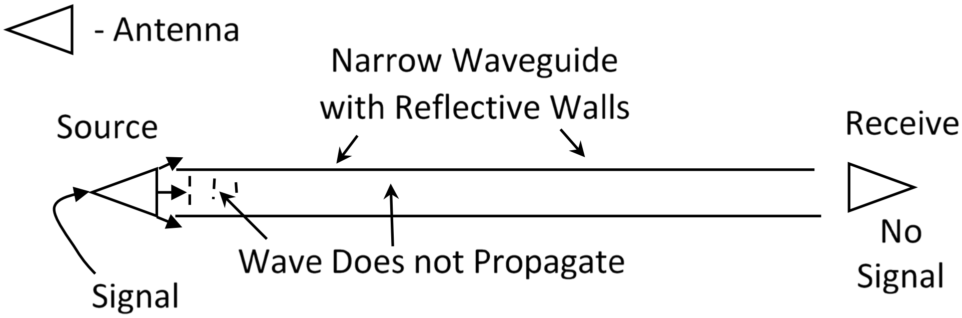


Figure 25 Waveguide with reflective walls does not transmit waves with frequencies below the cutoff frequency

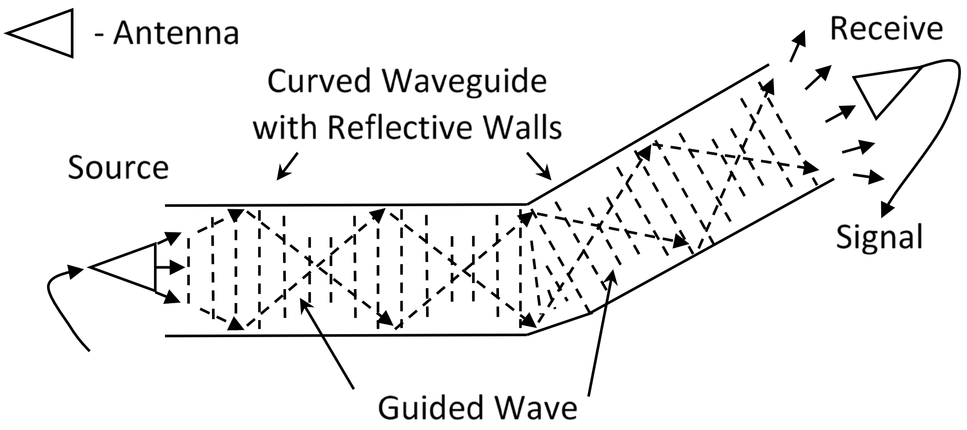


Figure 26 Curved waveguide with conductive walls can transmit signals long distances

Culverts with concrete walls differ from conventional waveguides. The culvert walls, especially when wet, are highly absorptive and cause the culvert to lose the ability to guide electromagnetic waves. Properties of culverts with lossy concrete walls that differ from ideal waveguides include: 1. The concrete walls absorb energy from the waves and cause them to attenuate rather than reflect and propagate, Figure 27; 2. Curved culverts send waves directly into the walls at the bends which increases losses and prevents long distance signal transmission, Figure 28; and 3. Waves only travel effectively in straight culverts by line-of-sight transmission along straight beams, Figure 27 [Delogne 1991]. These conclusions agree with the observation that the small diameter concrete culverts have the shortest telemetry transmission ranges.

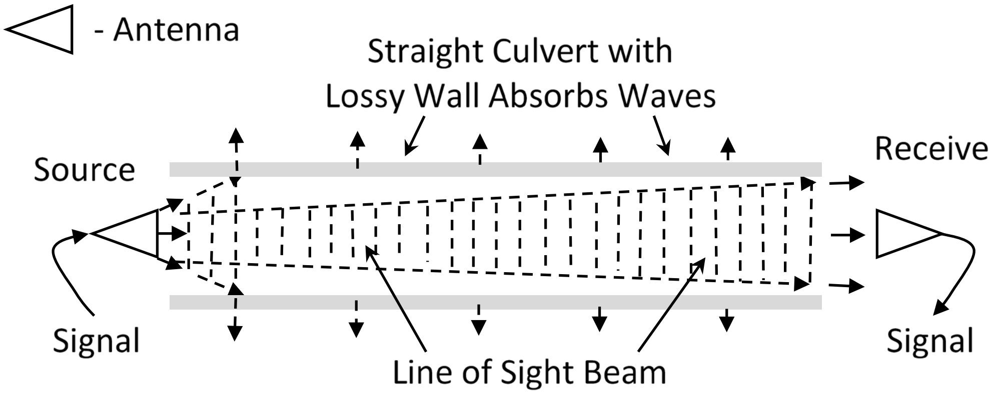


Figure 27 Straight culverts with lossy walls do not guide electromagnetic waves but do allow transmission along line-of-sight beams

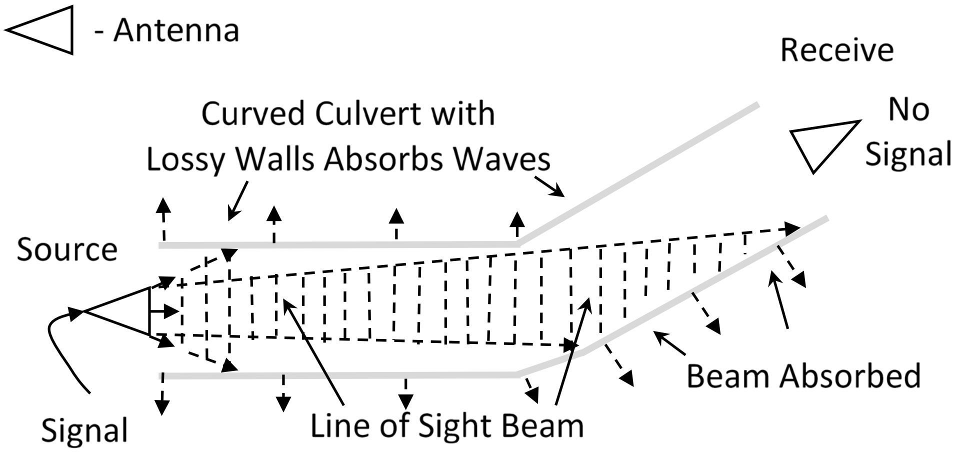


Figure 28 Curved culverts with lossy walls prevent transmission of electromagnetic waves by failing to guide waves and absorbing line-of-sight beams

Culverts with DIs have geometries and signal transmission properties similar to curved waveguides with lossy walls. The walls of a DI absorb the waves of a line-of-sight beam that propagate along a straight culvert. This prevents signal transmission to an antenna positioned at the top of the DI near a utility hole, Figure 29. The placement of an antenna into the path of the line-of-sight beam with the use of an extension cable by inserting through a utility hole enables signal transmission through the DI, Figure 30. An alternative that permits the use of more than one antenna, such as for video and RC signal transmission, is to insert a reflector dish into the DI to redirect the line-of-sight beam up through the utility hole for top side access, Figure 31.

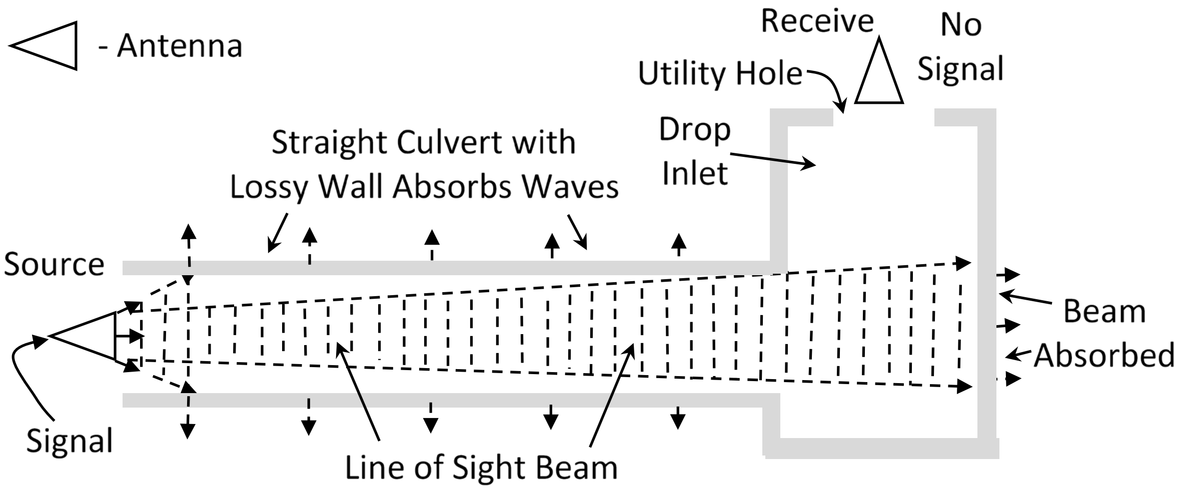


Figure 29 Culvert with drop inlet geometry, losses combine with geometry to prevent signal transmission through utility hole at top

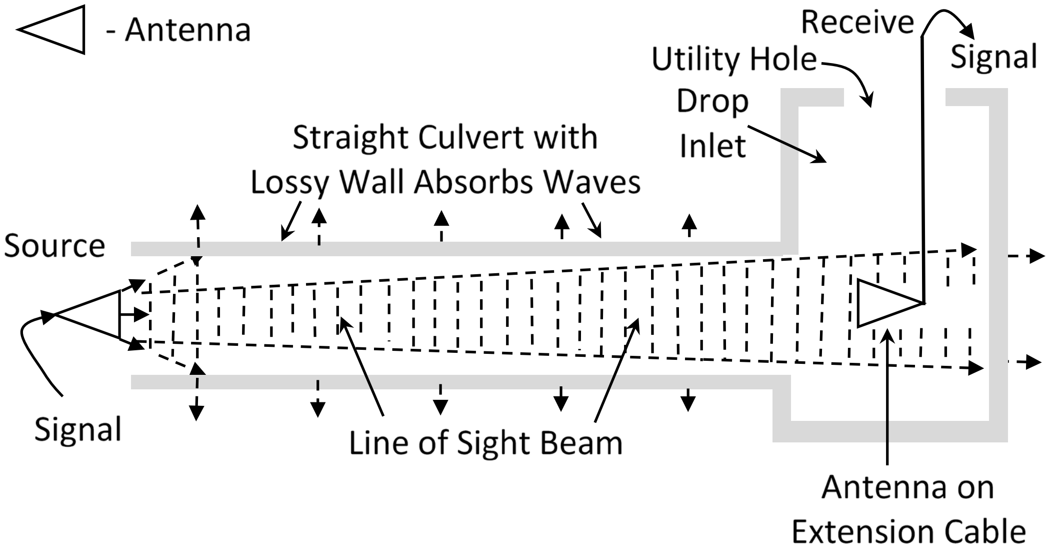


Figure 30 Insertion of antenna on extension cable through drop inlet utility hole access allows for line-of-sight signal transmission in straight culverts with lossy walls.

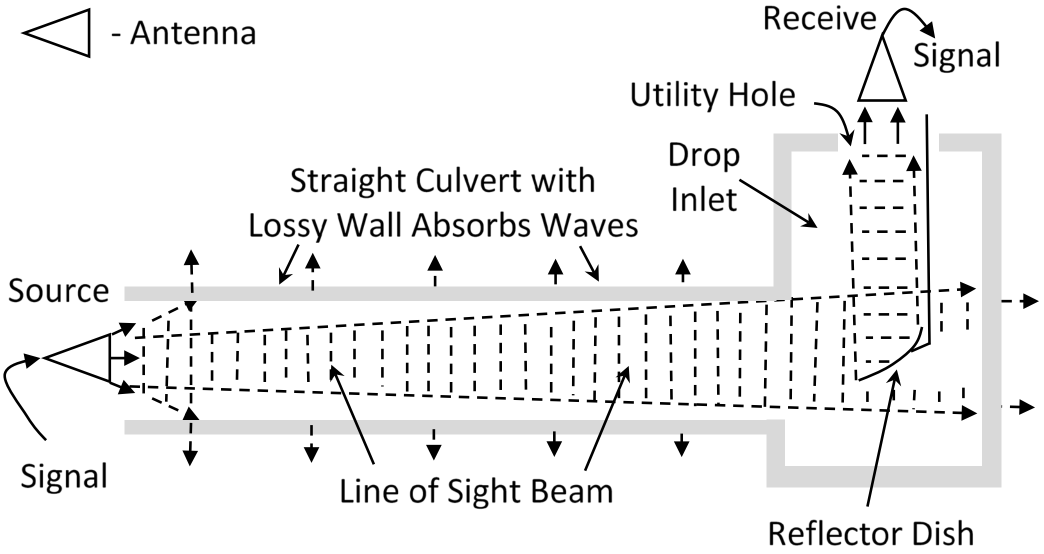


Figure 31 Insertion of reflector dish on pole through drop inlet utility hole redirects line-of-sight beam to enable topside signal transmission and reception.

3.7 Telemetry Options

A primary deficiency of the HIVE 1.0 was the telemetry range, especially for the video signals with the desired range being at least 30.5 m (100 feet) into an 0.457 m (18 inch) culvert. Additionally, being able to operate the vehicle through a DI is a primary concern. Methods of extending the transmission range were explored through a combination of analysis and prototype testing of concepts. The mode of the extended range transmission could be either wireless or wired. Both methods have advantages and disadvantages. A wired system has a cable that adds weight and resistance to the vehicle as it moves through the culvert but has the potential to simplify the electronic interface. Wireless extended range transmission simplifies the cable design by keeping the existing tether, but requires modification to the electronics, including the power supply. Frequency bands with readily available hardware are 1.2, 2.4 and 5.8 GHz. Electromagnetic waveguide theory suggests that these three transmission frequencies are above the cutoff frequency and should transmit through a 0.457 m (18 inch) culvert, when it acts as a waveguide. Based on these considerations it was decided to try telemetry systems operating at 1.2, 2.4 and 5.8 GHz to see if a viable link could be found under field conditions that did not impose significant weight and power penalties. The first set of extended range telemetry tests used the HIVE 1.0 platform to assess the capabilities of the various options.

The video telemetry options at 1.2 GHz are somewhat limited. Transmitters and receivers at 1.2 GHz generally are used for closed-circuit television (CCTV) video surveillance and tend to be too large to mount on a vehicle for small culvert inspections. There was one small system available, Figure 32. The yellow device is the transmitter which mounts to the vehicle, while the grey device is the receiver which connects to the monitor. This system has an output power of 1.5 W and an advertised range of 965 m (0.6 miles) in open space. The transmitter has dimensions of 12.7 x 50.8 x 102 mm^3 (0.5 x 2 x 4 $inches^3$). The system costs $70.

Figure 32. 1.2 GHz video transmitter and receiver

The Sony Action Cam on the Hive 1.0 provides a convenient means of assessing the performance of telemetry at 2.4 GHz, Figure 2.

Transmitters and receivers that use the 5.8 GHz band are widely available. The hobby of first-person view (FPV) drone racing has led to the availability of many small wireless transmission cameras. Most of the FPV cameras operate at 5.8 GHz. Two cameras selected for detailed evaluation and testing are small and can easily mount to the chassis of the HIVE 2.0 tank. Figure 35 shows an integrated camera and 5.8 GHz transceiver. The power output of the transmitter can toggle between 25, 50, and 200 mW and costs only $17. However, the camera has a TVL specification of 600 which is on the lower end of desired image resolution. A Foxeer camera provided a TVL of 1200 in a form factor small enough for a HIVE, but did not have an integrated telemetry unit, Figure 33. The image received from this camera is high quality and provides detailed information about conditions inside the culvert, Figure 34. A separate 5.8 GHz transmitter connects to the camera to transmit the video. The camera and transmitter costs around $70.

Figure 33 Foxeer Falkor camera

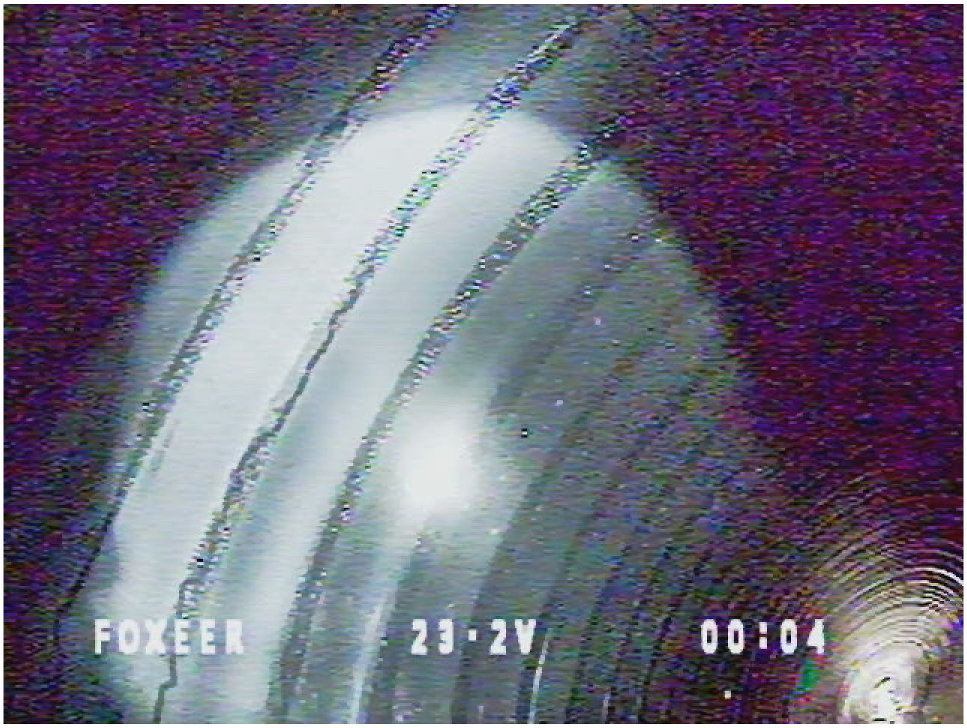


Figure 34 Sample of video telemetry inside culvert by Foxeer Falkor camera

Figure 35. Camera with integrated 5.8 GHz transmitter

3.8 Performance Evaluation of Telemetry Options

A series of tests evaluated the performance of the various telemetry options inside culverts with challenging geometries, including those with small diameters and DI configurations. These tests proceeded in parallel with the mechanical development of the HIVE 2.0 chassis and often made use of the HIVE 1.0 to transport the cameras and transmitters into the culverts.

3.8.1 Telemetry Option Test 1

The goal was to determine which of the three different video transmission systems (1.2, 2.4 and 5.8 GHz) provides the longest range in an 18 inch (0.457 m) concrete culvert. Culvert 64104 shown in Figure 36 off Route 7 in Charlotte, VT was chosen for its length of 30.8 m (101 feet) and ease of access. At the time of this test the HIVE 2.0 prototype was not waterproofed, the tests used the HIVE 1.0 to carry the various telemetry options into the culvert, Figure 37. The tests of 5.8 GHz telemetry used the integrated camera and telemetry system in Figure 35 since it was inexpensive and easy to set up.

Figure 36. Telemetry Option Test 1 Culvert ID: 64104, 0.457 m (18 inch) diameter, 30.8 m (101 feet) long, concrete, U.S. Route 7, Charlotte, VT

The testing protocol was first was to mount an individual monitor telemetry system onto the HIVE 1.0, then drive the HIVE 1.0 into the culvert until the video signal failed or became unreadable. Winding the spool of cable shown in Figure 37 retrieved the HIVE 1.0. Counting the revolutions needed to retrieve the HIVE 1.0 and using Equation (5) with a spool diameter of 127 mm (5 inches) determined the distance traveled into the culvert.

$$\mathbf{Distance\ (m) = \#Revolutions\ [0.127\pi]} \tag{5}$$

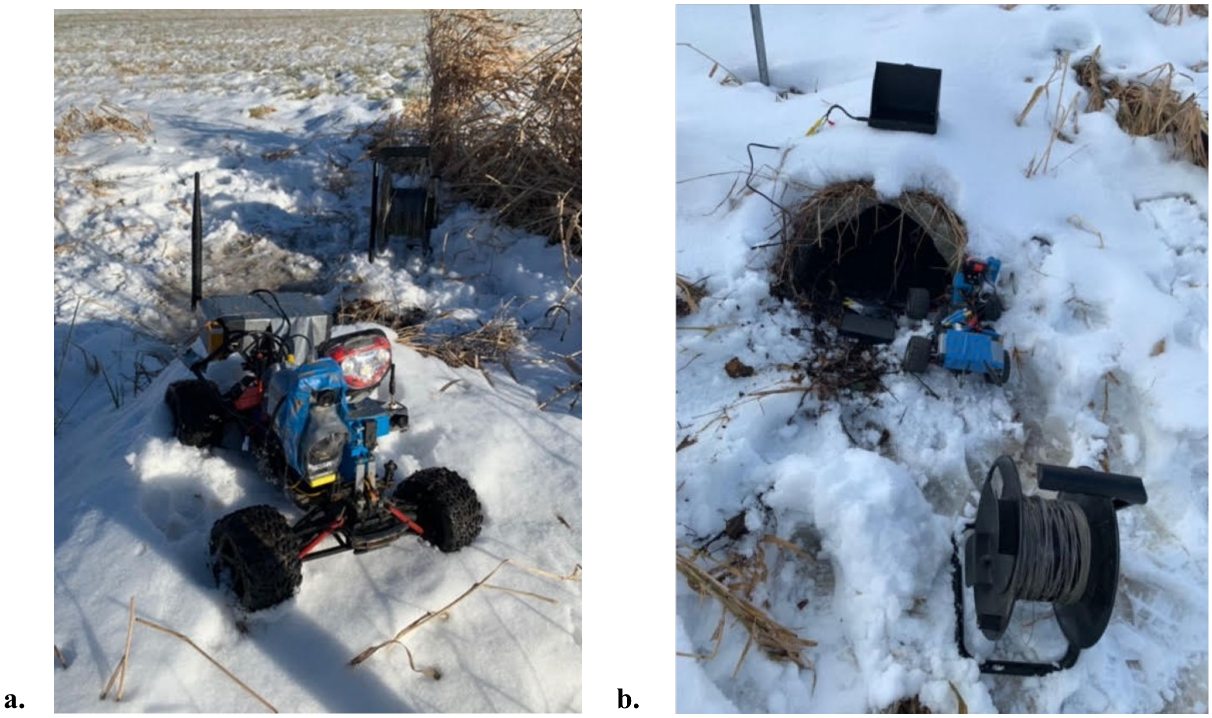


Figure 37 Telemetry Option Test 1 using HIVE 1.0 instrumented with 1.2, 2.4, and 5.8 GHz video systems: a. HIVE 1.0 with added telemetry options, and b. Setup with telemetry modules and retrieval wire spool

Figure 38 shows the results of Telemetry Option Test 1. The 5.8 GHz system performed best, transmitting 25.0 m (82 feet) until the HIVE reached a clogged section of the culvert. If the HIVE 1.0 could have driven further, the 5.8 GHz system may have been able to transmit even further. The 1.2 GHz system transmitted up to 14.0 m (46 feet) which is substantially less than the capability of the 5.8 GHz system. However, these two systems showed significant improvement over to the original 2.4 GHz system of the HIVE 1.0 which transmitted only 7.62 m (25 feet).

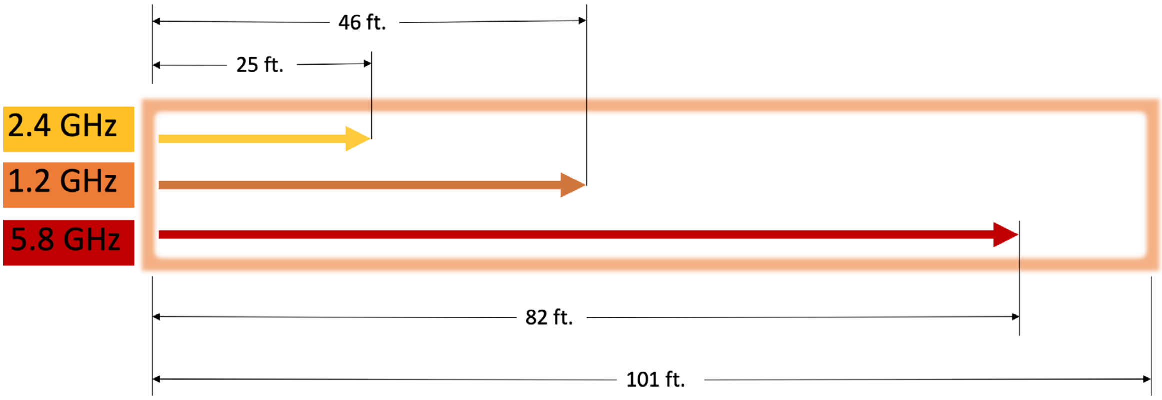


Figure 38 Telemetry Option Test 1 results showing range of different video transmission frequencies

These results show that the 5.8 GHz system has the longest range when compared to the 1.2 and 2.4 GHz systems in a 0.457 m (18 inch) concrete culvert. The results also show that video transmission range depends on more than transmission frequency, as the range of the 2.4 GHz system does not fall between that of the 1.2 and 5.8 GHz frequencies. The transmission power level also affects the range of transmission. For this test, each system operated at different power levels, nominally being set by the operational hardware that complies with FCC regulations. Conducting a test to find the optimum frequency and power level combination is not practical due to the constraints of the commercially available hardware. The video transmission systems in the 1.2 and 2.4 GHz range do not allow for selecting a range of power levels. Many 5.8 GHz systems provide a selectable range of transmission power from 25 mW to 1000 mW.

3.8.2 Telemetry Option Test 2 Video Range Test, 0.762 m (30 inch) Culvert

The purpose of this test was to determine whether the 5.8 GHz system still outperforms the 1.2 GHz system in a 0.762 m (30 inch) diameter culvert. The testing did not include the 2.4 GHz system since the transmission range in the 0.457 m (18 inch) culvert was far below the necessary range of 30.5 m (100 feet) per the design requirements. Culvert 64099 off US Route 7 in Charlotte, VT was chosen for its length of 51.2 m (168 feet) and ease of access, Figure 39.

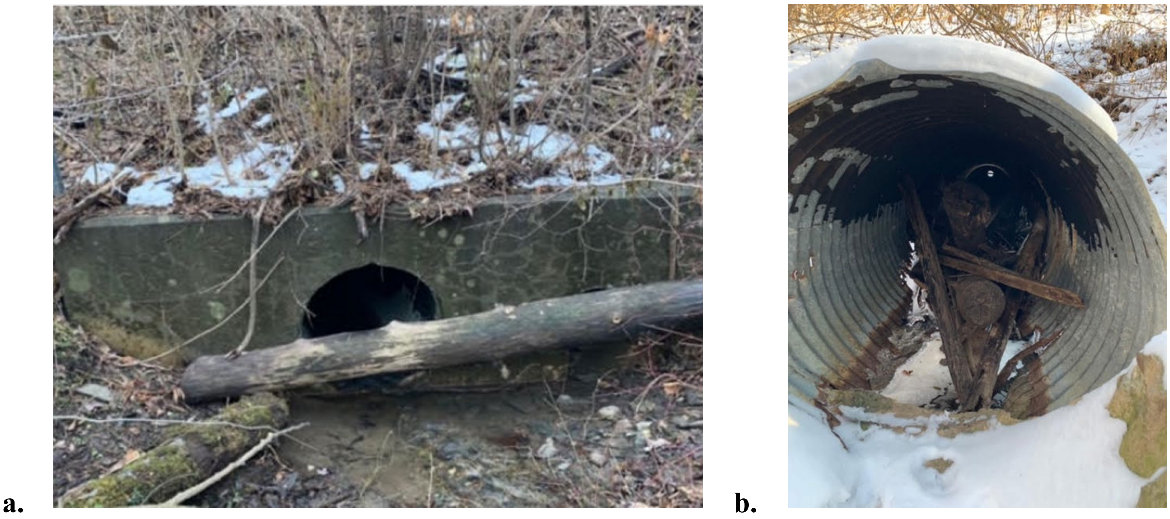

a. b.

Figure 39. Telemetry Option Test 2 Culvert ID: 64099, 0.762 m (30 inch) diameter, 51.2 m (168 feet) long, metal liner: a. Entrance, and b. Internal debris

The protocol for Telemetry Option Test 2 was similar to that of Telemetry Option Test 1 with the telemetry systems placed on the HIVE 1.0 as it drove through a measured distance into the culvert, Figure 40.

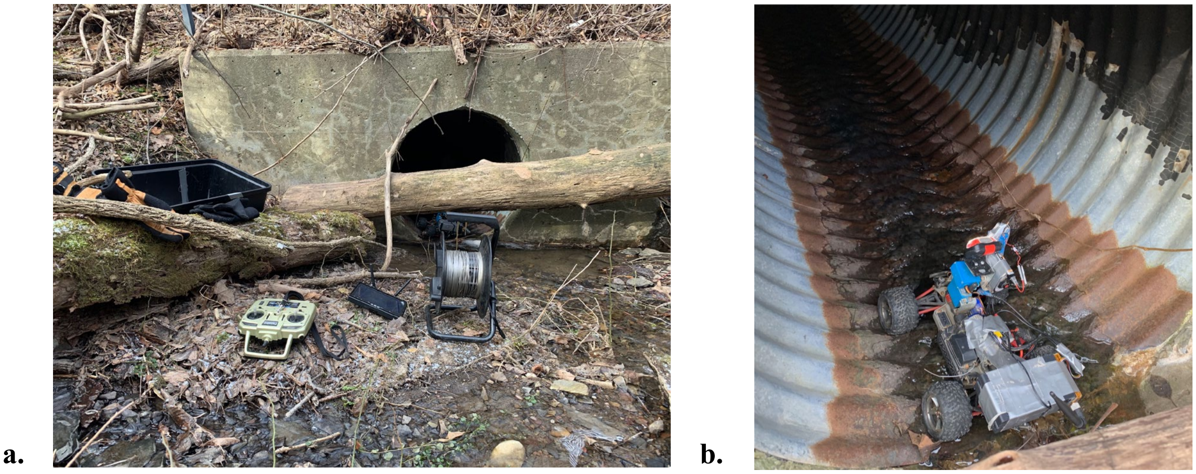

a. b.

Figure 40. Telemetry Option Test 2 setup, HIVE 1.0 instrumented with 1.2 and 5.8 GHz video systems placed inside Culvert 64099 entrance for reception test at the other end

The first run of Telemetry Option Test 2 used the 1.2 GHz telemetry system for the video monitor. The modified HIVE 1.0 made it 43.9 m (144 feet) until a wheel became stuck in a separation gap in the culvert. After many failed attempts of driving and pulling the vehicle from the steel cable, the HIVE 1.0 was eventually retrieved by crawling into the culvert from the exit. To avoid the risk of getting the HIVE stuck a second time, a pass-fail test was conducted to test the 5.8 GHz system. This test placed the HIVE just inside the entrance of the culvert as shown in Figure 40, and walking over to the exit to see if the video would transmit the entire length of the culvert, Figure 42.

Figure 41 HIVE 1.0 stuck in separation gap of Culvert 64099, vehicle headlamp is visible.

Figure 42 Test 2 setup, monitor at exit of Culvert 64099 with vehicle at entrance

The video signal received at the exit of the culvert shows that the 5.8 GHz system can transmit at least 51.2 m (168 feet) through a 0.762 m (30 inch) culvert. The 1.2 GHz system can provide a range of at least 43.9 m (144 feet) in the 0.762 m (30 inch) culvert. Figure 43 summarizes the results. The 5.8 GHz system was the top performer in the 0.457 m (18 inch) culvert and transmitted much further than the required 51.2 m (168 feet) in the 0.762 m (30 inch) culvert.

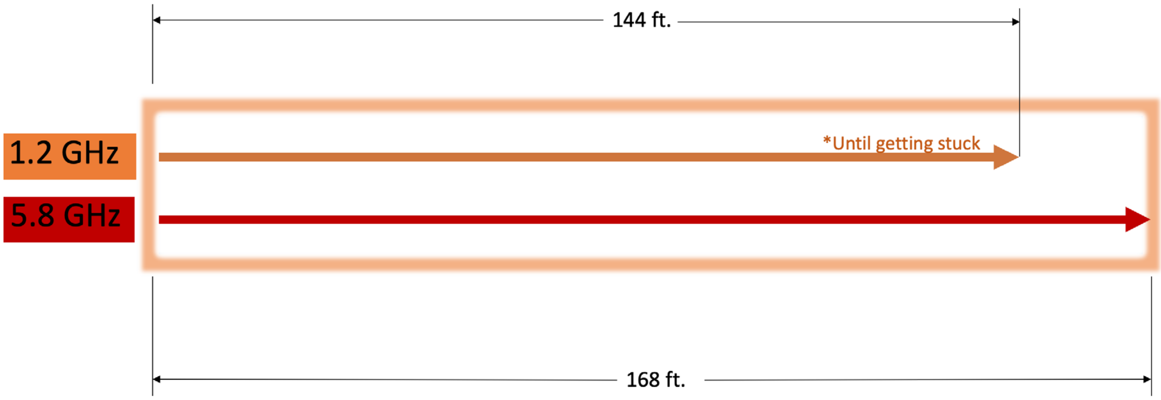


Figure 43 Test 2 results showing range of different video transmission frequencies

The results of Telemetry Option Tests 1 and 2 confirmed that 5.8 GHz system was the best available band for telemetry in small culverts. This motivated the selection of 5.8 GHz as the telemetry band for the video monitor signals in subsequent tests.

3.8.3 Telemetry Option Test 3: Video Range Test, Drop Inlet

This test determined whether the 5.8 GHz telemetry system could transmit 23.4 m (80 feet) into a culvert though a DI as required in Specification 4 of Table 2. A DI is an inlet to a culvert that allows water to enter through a grate covered utility hole on the surface of the ground and down into the culvert. A key distinction is that the geometry of the DI prevents an easy direct line-of-sight path for the video signal from a HIVE in a culvert to a receiver at the top of the inlet. Instead, the signal scatters off and absorbs into the walls of the DI, substantially reducing the power and decreasing the range.

The DI video telemetry tests used Culverts 161158 and 161150 off US Route 7 in Ferrisburgh, VT. Both culverts have a DI, a diameter of 0.762 m (30 inch) with an HDPE liner, and sufficiently long lengths of 44.2 m (145 feet) and 46.3 m (152 feet), respectively. The culverts appear on the left side of Figure 44. The arrows represent the culverts, and the pink squares represent the DIs. The pink square boxed in a blue rectangle is denoted the Middle DI and the other the Inlet DI.

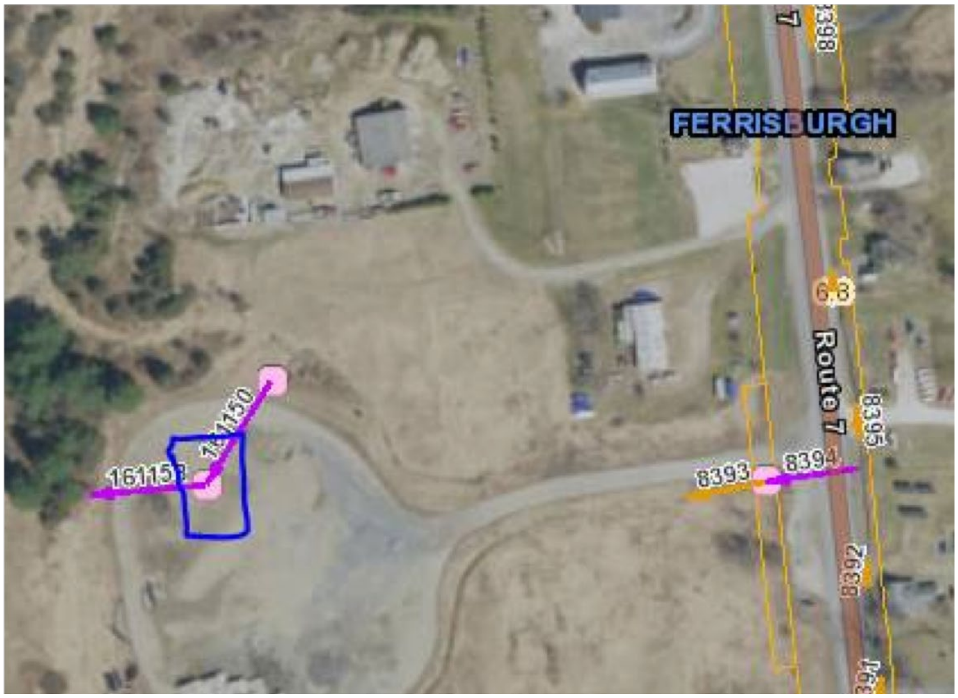


Figure 44 Culvert ID: 161158 and 161150, 0.762 m (30 inch) diameter, 44.2 m (145 feet) and 46.3 m (152 feet) long with HDPE liner. Arrows correspond to culverts, and pink squares correspond to drop inlets.

Ideally the video telemetry test would follow the same protocol used in Telemetry Option Test 1 and Test 2, where the tests begin with inserting the HIVE into the culvert through the DI. However, these DIs extend 0.610 m (2 feet) deeper than the depth of the culverts. This makes placing the vehicle into the culvert through the DI very difficult. To avoid this issue, Telemetry Option Test 3 became a quick pass-fail test similar to the second method of Telemetry Option Test 2. Figure 45 illustrates the setup.

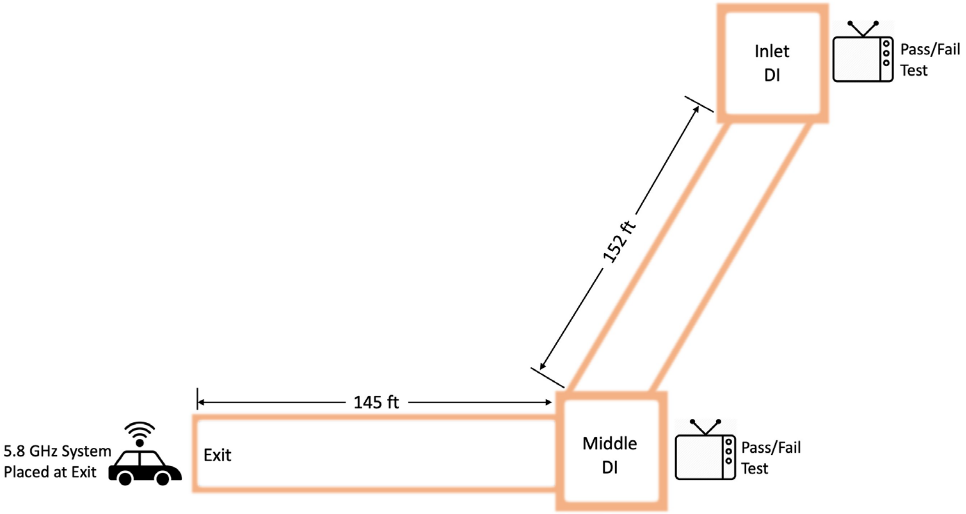


Figure 45 Telemetry Option Test 3 setup

Figure 46 shows the HIVE 1.0 at the exit modified to carry a 5.8 GHz video system, and the monitor placed above the middle DI to check for reception. The first step checked the reception at the middle DI. The next step checked the reception at the inlet DI. The video transmitter output power level was 25 mW.

The results of Telemetry Option Test 3 were that the video signal was received at the middle DI with the HIVE 44.2 m (145 feet) away, but not at inlet DI about 91.4 m (300 feet) away, Figure 47.

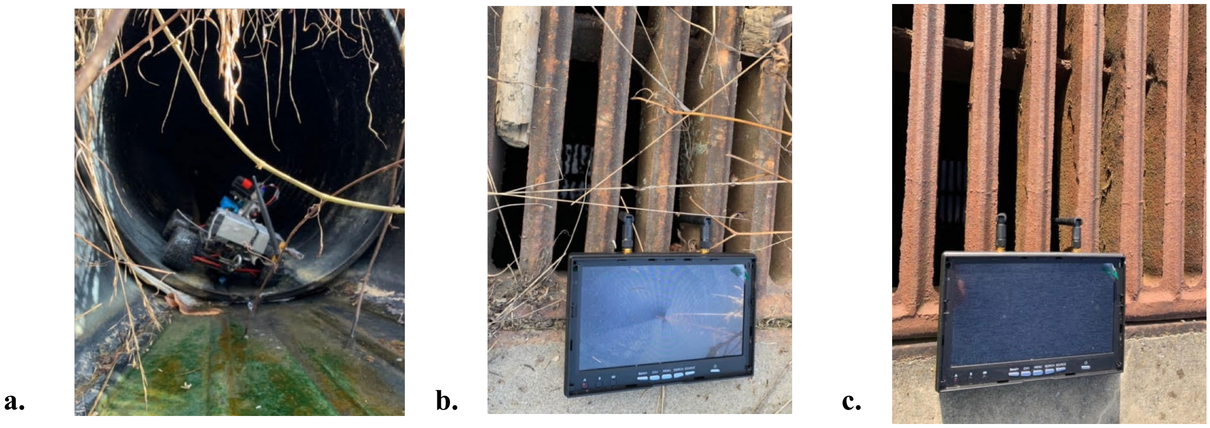


Figure 46. Telemetry Option Test 3 5.8 GHz video transmission options: a. HIVE 1.0 at exit of culvert, b. Video monitor at middle drop inlet, and c. Video monitor and entrance drop inlet

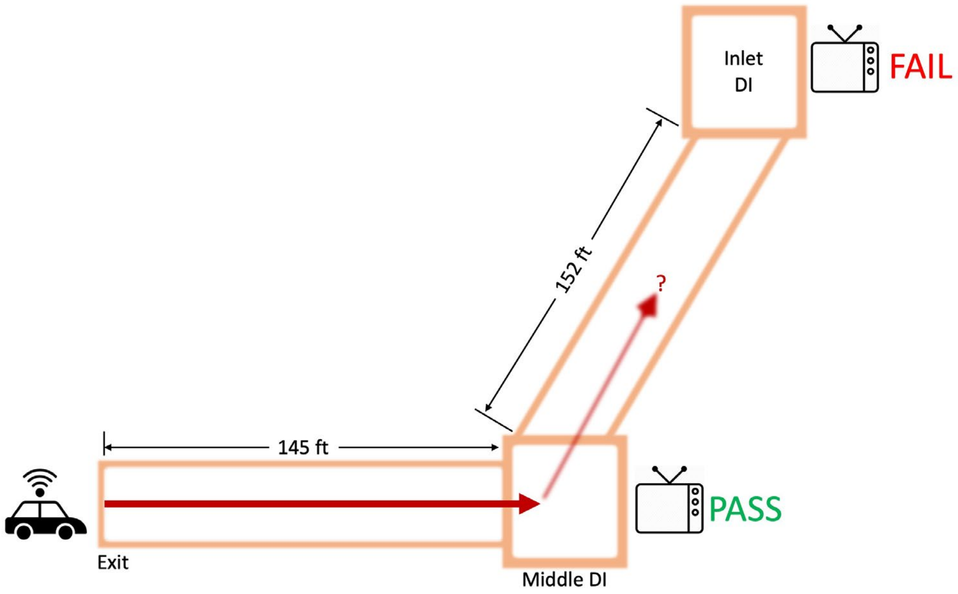


Figure 47 Telemetry Option Test 3 results showing pass-fail results of 5.8 GHz transmission

These results show that the 5.8 GHz system can meet the specification of transmitting the video at least 24.4 m (80 feet) through a DI. The video reception improved by orienting the antennas on the monitor down through the grate of the DI. Transmission power levels larger than 25 mW could increase this range. However, excessively high-power outputs reduce battery life. A recommended output level is 50 mW when operating in culverts.

The transmitter has built in DVR capability that saves to a TF card. The transmitter and receiver use omni-directional antennas for effective video telemetry, even when the two antennas have different relative orientations. The hardware introduces a flexibility where the operator can choose to monitor the video through a 5.8 GHz monitor, or a 5.8 GHz receiver connected to either an iOS or Android device. Both options allow for recording the video and saving on the monitoring device. Multiple receivers can simultaneously pick up the video transmission for multi-viewer applications. Using only one transmitter for the two cameras extends the battery life.

3.8.4 Telemetry Option Test 4: Video Range Test, Drop Inlet with Range Extenders

The aim of this test was to determine the optimal transmitter output power between 25 and 200 mW, confirm the functionality of a monitor antenna extension cable, and determine the optimal antenna type between linear and circular antennas. The test site was again Culverts 161158 and 161150 with DIs in Ferrisburgh, VT. Figure 48 illustrates the test layout and geometry, which was similar to Telemetry Option Test 3 with transmission through the DIs.

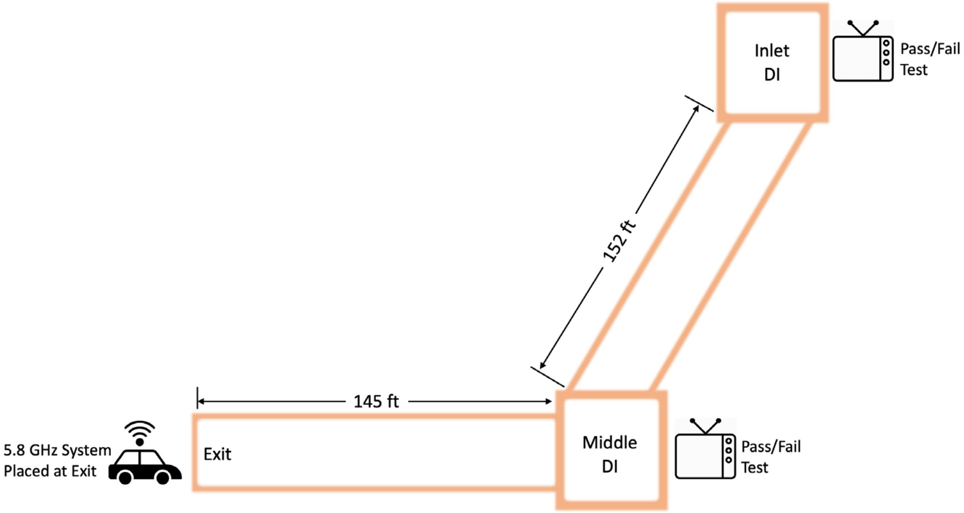


Figure 48 Telemetry Option Test 4 layout geometry

The test used the HIVE 2.0 Sherman tank chassis to carry the telemetry options into the culverts, Figure 17. The first step placed the tank at the exit of the culverts and then monitored the reception at the two different DIs for the two different power levels of 25 and 200 mW. The evaluation examined the reception at the DIs using the different antenna types. First, the measurement was an inspection of the signal was inspected with the antenna above ground at the DIs. The next measurement compared to the reception with one antenna suspended from a 0.914 m (3 foot) coaxial extension cable down into DI as shown in Figure 49. The test examined both the linear and circular antenna types.

Figure 49 Telemetry Option Test 4 Monitor with antenna placed into line of sight of culvert exit using coaxial extension cable in DI

When testing the different power output levels, both made it to the middle DI. Only the 200mW power level produced a visible signal when monitoring at the inlet DI, Figure 50.

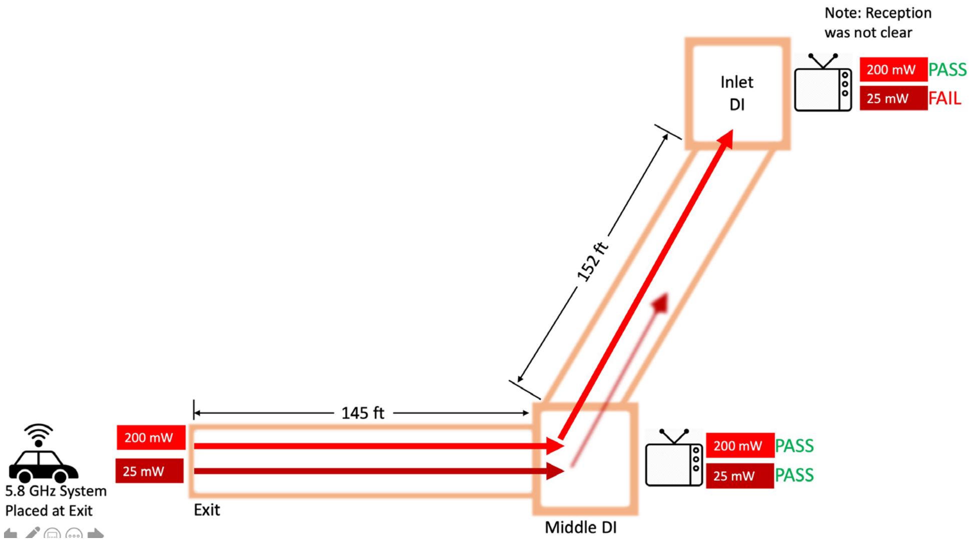


Figure 50 Telemetry Option Test 4 results

A subsequent analysis indicated that these results were misleading. When viewing the signal at the inlet DI with a 200 mW power output level, the assumption was that the signal traveled through the culvert-DI-culvert path. However, a later test indicated that as the 5.8 GHz system traveled further into the culvert and shortened the through culvert distance to the receiver, the reception at the inlet degraded. Conversely, placing the system at the edge of the exit of the culvert improved the video signal reception at the inlet DI. This showed that the video signal did not travel through the culvert-DI-culvert path but instead traveled outside the culvert over the ground. This was not the case for inspections at the middle DI since the signal has line-of-sight connection through the culvert. A follow-on test would be to test higher transmission power levels to see if they could transmit from the exit to the inlet DI.

Using the antenna extension cable greatly improved the signal reception through a DI. Figure 51 shows the difference in reception when the antenna extension cable is used. An important detail is the monitor configuration. The monitor setup uses two antennas. Each antenna has a separate signal path. The monitor automatically selects that best of the two signals to display on the monitor. The illuminated blue light above the screen of the monitor indicates which antenna is providing the signal. Figure 51.a shows the illuminated blue light is on the right indicating that the right antenna is receiving the signal, not the left antenna with the extension cable. The picture in the monitor is granular. It is difficult to make out the image being displayed. Figure 51.b, with the extension cable positioned to place the antenna into the DI, shows that the illuminated blue light on the left antenna is now receiving the signal. The picture has cleared up sufficiently to reveal a view of the inner wall of the culvert.

a. **b.**

Figure 51 Telemetry Option Test 4 results comparison between antenna in and out of DI: a. Antenna out of DI, b. Antenna in DI

These results confirm that an antenna extension cable dropped into a DI and placed into the line of sight of the HIVE in the culvert is an effective method for enhancing the signal reception a DI. There was hardly any noticeable difference in performance with the linear and circular antennas. However, circular antennas send and receive signals in an isotropic pattern. The performance of the circular antennas is independent of orientation, which favors selection in the final design.

3.8.5 Telemetry Option Test 5: Effect of Transmission Power on Video Reception

The goal of this test was to characterize further the effect of transmission power on video reception. The test used a transmitter with a power output level up to 1000 mW to see if high power transmission improves transmission range. Telemetry Option Test 5 used the same test locations, as Telemetry Option Test 4, i.e. Culverts 161158 and 161150 with the DIs off US Rte. 7 in Ferrisburgh, VT. The test examined the use of signal power output levels of 25 mW, 200 mW, 600 mW, and 1000 mW. The test began with driving the HIVE 2.0 tank system 38.1 m (125 feet) into the culvert from the exit, and then monitoring the video signal reception as the tank was pulled back toward the exit, Figure 48. The receiver configuration was an antenna attached to an extension cable, dropped down the DI and placed into the line of sight of a culvert, as in Figure 49. When the monitor lost the video signal, recording the distance of the tank determined how far the video transmitted for each power level. The test examined performance at both the middle DI and then the inlet DI. Figure 52 illustrates the setup.

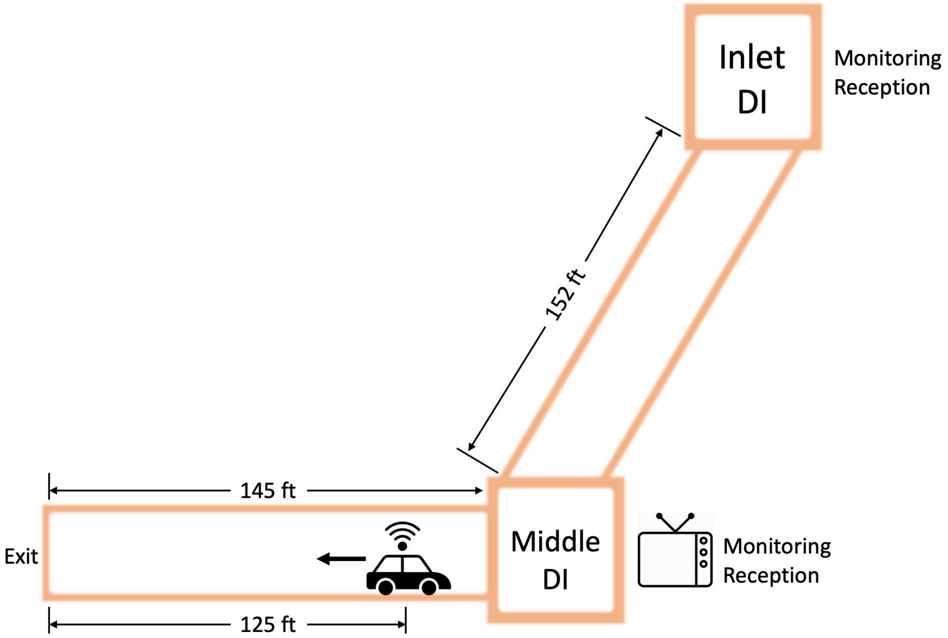


Figure 52 Telemetry Option Test 5 setup

The results of Telemetry Option Test 5 were that with the HIVE 2.0 tank at an initial position, 38.1 m (125 feet) into the culvert, none of the power levels ranging from 25 mW to 1000 mW were able to transmit the video from the exit culvert to the corner at the middle DI into the inlet culver to the receiver at the inlet DI. However, all power levels transmitted the video from the exit culvert to the middle DI. The 25 mW power level provided a slightly less consistent image. Figure 53 summarizes the results.

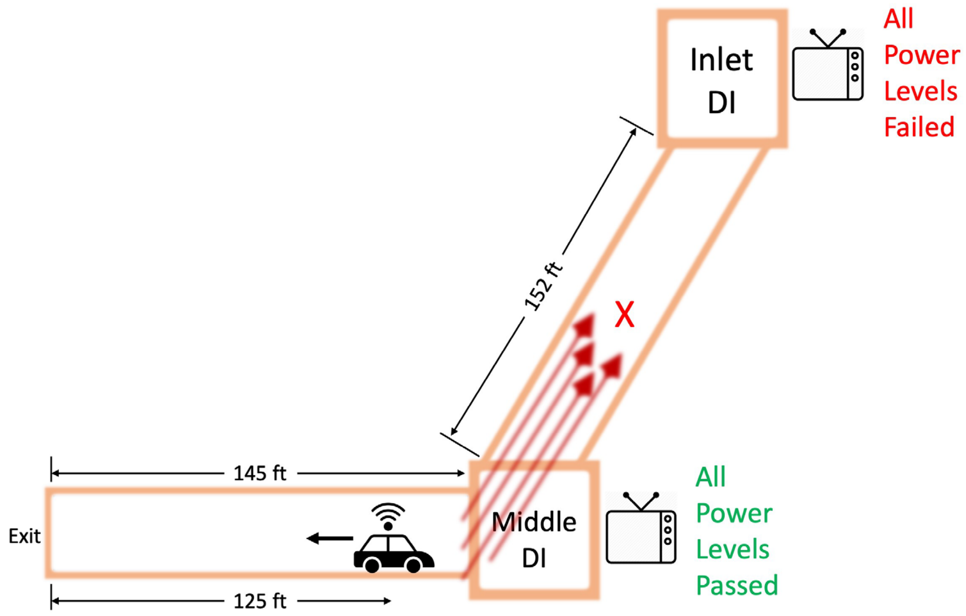


Figure 53 Telemetry Option Test 5 video transmission results

These results show that the video loses significant power after reflecting off surfaces and changing direction in the DI. This helps to characterize better the limitations of the 5.8 GHz video transmission system. If operating in a straight culvert, the video can transmit at least 44.2 m (145 feet) through a DI, which exceeds 24.4 m (80 feet) distance of Performance Specification 4 in Table 2. However, the RC signal range of the culvert inspection vehicle then becomes the primary range constraint on the HIVE 2.0. During the setup, the tank was able to drive only 38.1 m (125 feet) into the culvert because the RC connection to the tank cut out. This range of 38.1 m (125 feet) still exceeded the 24.4 m (80 feet) distance required by Performance Specification 3.

3.8.6 Telemetry Option Test 6: HIVE 2.0 Tank Remote Control Range Through Drop Inlet

This test determined the RC range of the HIVE 2.0 tank when operating through a DI. The setup was similar to Telemetry Option Test 5, as shown in Figure 54.

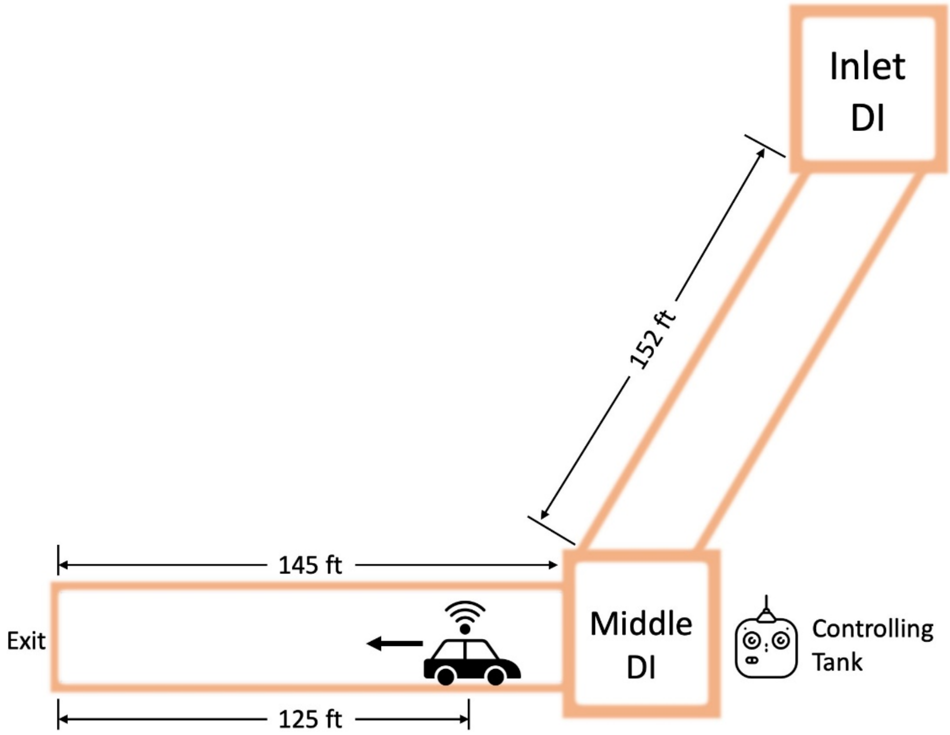


Figure 54 Telemetry Option Test 6 – HIVE 2.0 tank remote control range test setup

Telemetry Option Test 6 began by driving the HIVE 2.0 tank 38.1 m (125 feet) in from the exit of the culvert using line-of-sight telemetry with the RC at the exit to provide the control to achieve the range. The next step relocated the RC to the middle DI with a placement above the drain gate, Figure 55. Driving the tank back toward the exit until the RC signal cut out and then measuring the distance by counting revolutions of the retrieval wire spool determined the RC telemetry range. The tank travelled 21.9 m (72 feet) from the middle DI before losing the RC signal. Figure 56 illustrates this result, which did not pass the distance requirement of Specification 4 of being able to travel under control at least 24.4 m (80 feet) through a DI.

Figure 55 Tank remote held above middle DI grate to drive HIVE 2.0 tank back to exit

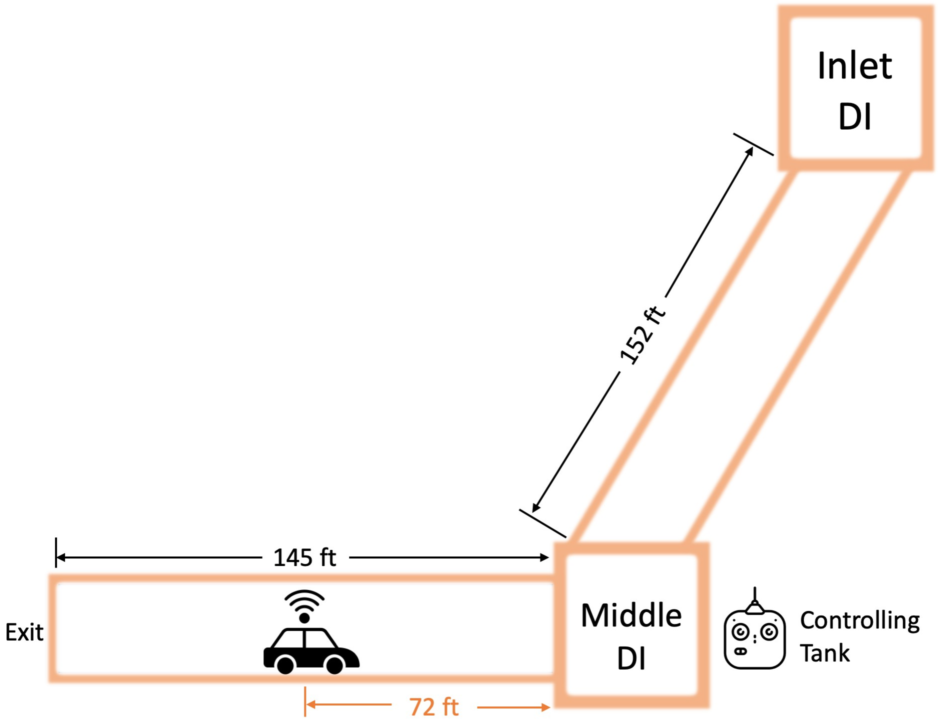


Figure 56 Telemetry Option Test 6 Remote Control range through drop inlet results

3.8.7 Telemetry Option Test 7: HIVE 2.0 Tank Remote Control Range with Modified Telemetry Hardware

This test determined the effects of modifications to the controller telemetry hardware of the HIVE 2.0 tank on the telemetry range. The modifications included removing the original antenna on the controller and replacing it with a soldered connection to a short SMA cable, Figure 57. The SMA cable allowed for the attachment of a 0.914 m (3 foot) antenna extension cable and a low noise amplifier, Figure 58. A second tank with an unmodified controller provided baseline data for comparison.

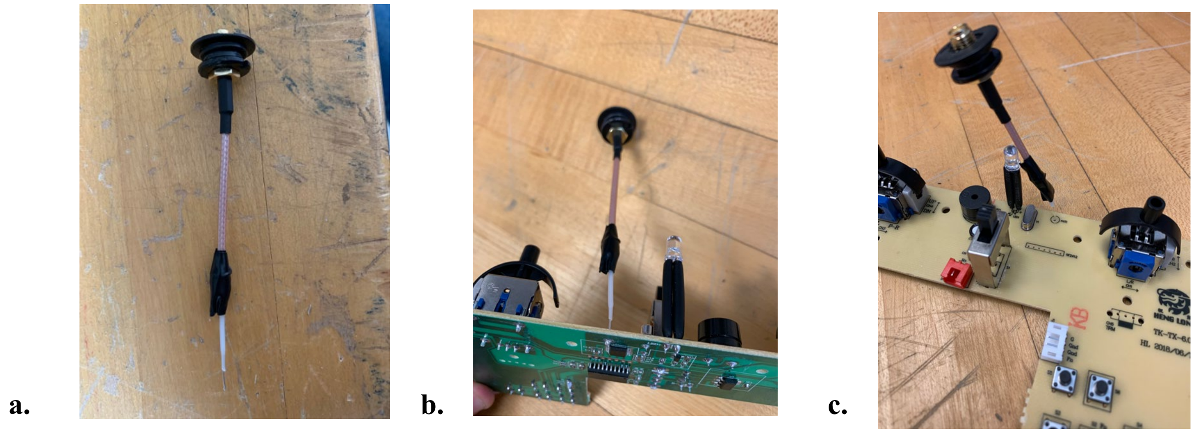


Figure 57 Modification of stock radio controller for tank: a. Extension pigtail cable, b. Insertion through PCB board, and c. Top view of completed attachment

Figure 58 Radio control unit modified with SMA antenna connector and extension cable attached to antenna for possible improved drop inlet telemetry

The test site was Culverts 161158 and 161150 in Ferrisburgh, VT with DIs. The setup first attached an antenna extension cable to the controller and then a low noise amplifier, Figure 59. The test protocol was the same as Telemetry Option Test 6, Figure 60. The controller drove the tank from the middle DI toward the exit until losing the remote connection. Counting the revolutions on the retrieval wire spool determined the distance traveled.

Figure 59 Telemetry Option Test 7 HIVE 2.0 controller modification effects on range: a. Unmodified controller, b. Controller with extension cable, and c. Controller with amplifier

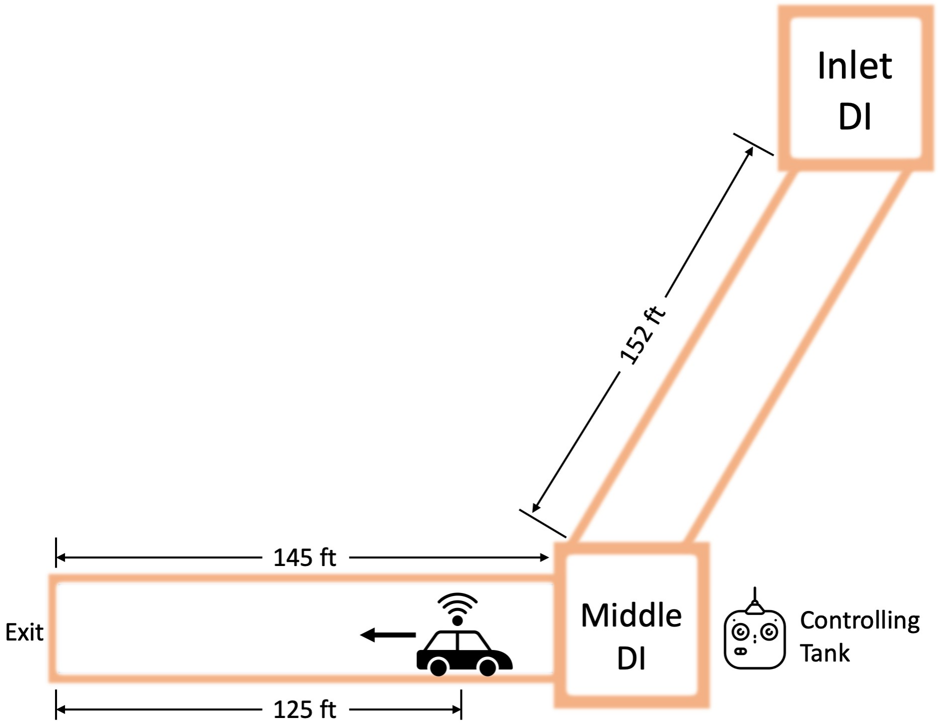


Figure 60 Telemetry Option Test 7 setup

Figure 61 shows the results of Telemetry Option Test 7. These are: 1. The test with the antenna extension cable attached to the controller resulted in a HIVE 2.0 tank travel distance of 31.1 m (102 feet); 2. Using the low noise amplifier produced a travel distance of 33.5 m (110 feet); and 3. The unmodified controller outperformed the modified versions with a travel distance of 34.1 m (112 feet).

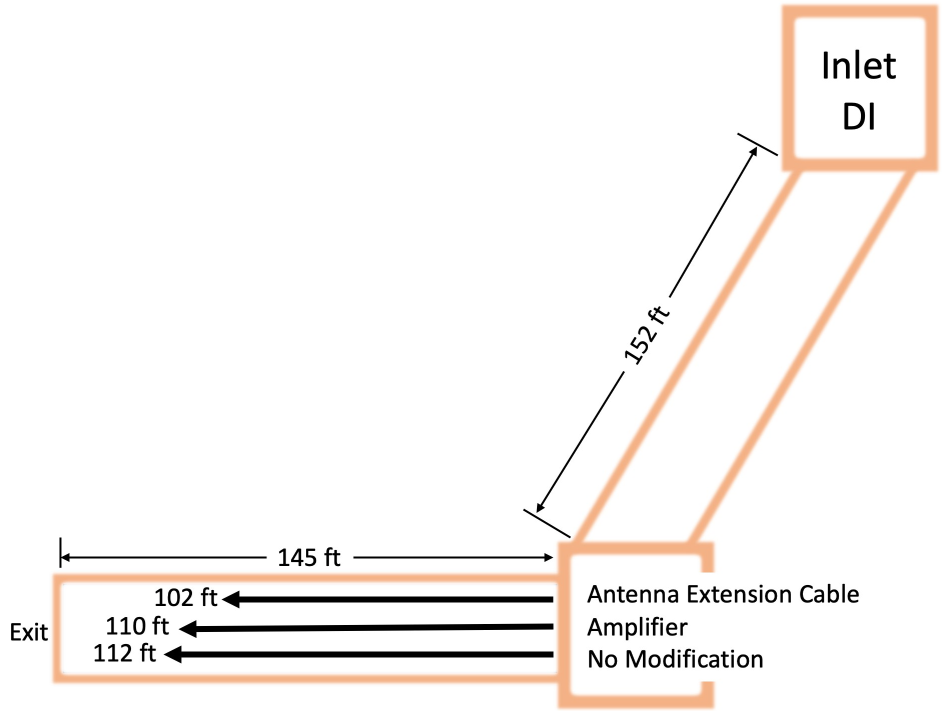


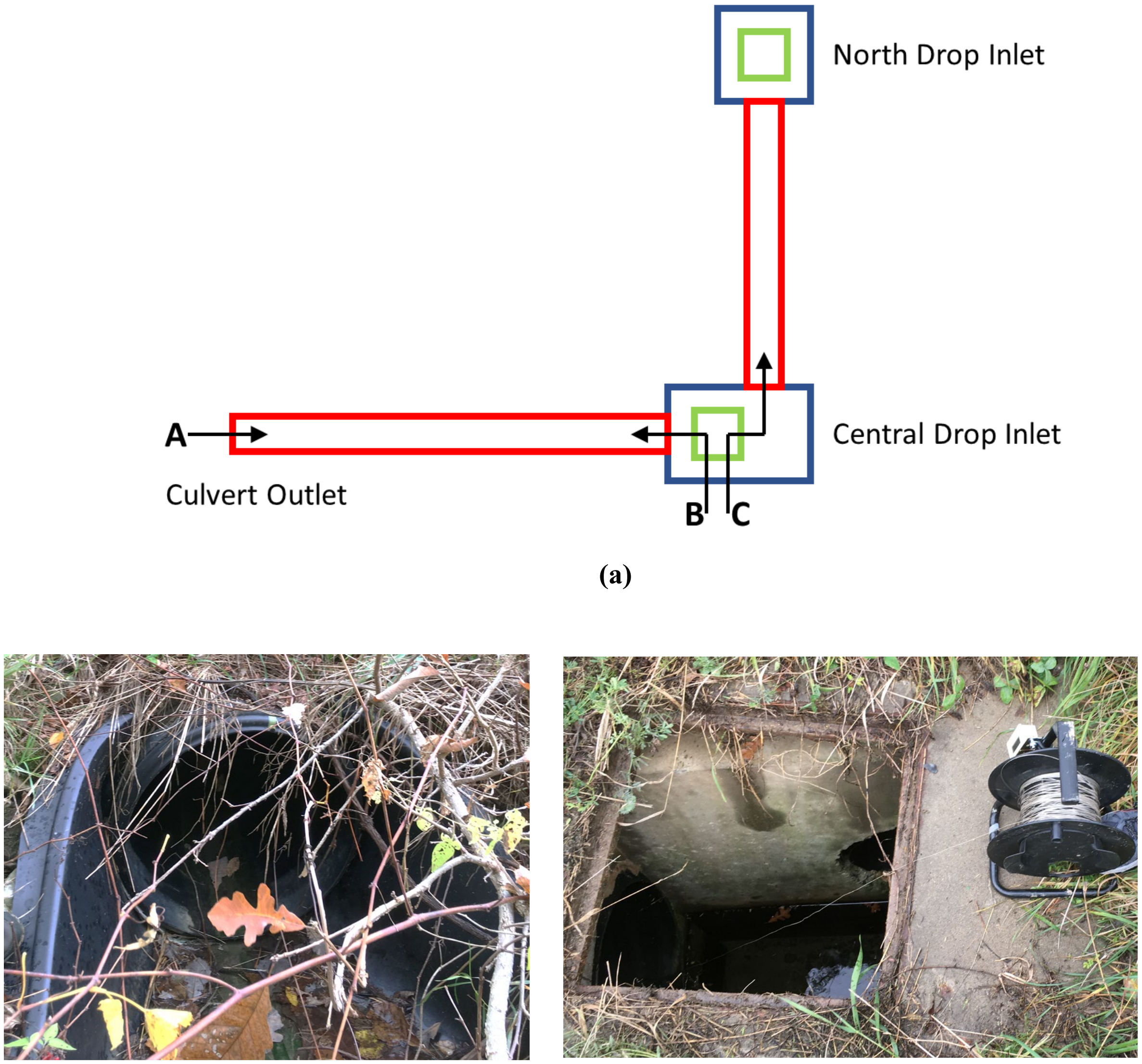
Figure 61 Results of Telemetry Option Test 7 remote control transmitter/receiver modifications

These results differ greatly from the tank range of 21.9 m (72 feet) from the first RC range test. This is due to the position the tank controller. During that previous test (Video Option Test 6), the tank controller was above the gate. In this test, the controller was down in the DI at an arm's length. When using the antenna extension cable, the controller position was not as deep into the DI as when testing with the amplifier and unmodified controller. This may explain the difference in range seen between the extension cable and amplifier. An alternative explanation is that the modified antenna attachment may be sensitive to uncompensated impedance and grounding effects. Nonetheless, these results show that the modifications did not improve the control range of the tank through a DI.

3.8.8 Telemetry Option Test 8: HIVE 2.0 Tank Video and Remote-Control Range Extension with Antenna Extension and Reflector Dish for Drop Inlets

The concept of carrying telemetry in culverts with electromagnetic waves propagating as straight beams along a line of sight motivates the use of antenna extensions and reflector dishes to extend both the video and RC range of the HIVE 2.0. The technique is direct insertion into the beam line, as shown conceptually in Figure 30 and Figure 31. An implementation appears in Figure 63, Figure 64, and Figure 65. The extension cable is an SMA coax. The reflector dish is an aluminum Direct TV antenna dish mounted onto a wooden broom handle. The test examined the ability of these modifications to extend the video and RC range of the HIVE 2.0 through a DI. The test site was Culverts 161158 and 161150 in Ferrisburgh, VT with DIs. The test protocol was the same as Telemetry Option Test 6, Figure 60, with the addition of the range extenders. The controller drove the tank from the middle DI toward the exit until losing the remote connection. Counting the revolutions on the retrieval wire spool determined the distance traveled.

Culverts 161158 and 161150 are 0.76-meter (30 inch) HDPE-lined culverts arranged in an "L" configuration with two concrete DIs, as shown in Figure 62.a. Accessing a culvert via a DI presents a challenge for HIVE inspection because the configuration of the DI disrupts line-of-sight from the operator to the culvert inspection vehicle, as in Figure 29. Line of sight is important for both video reception and remote-control functionality. Without a line of sight, signals must reflect off the absorptive concrete walls of the DI, reducing power and decreasing range. To overcome this challenge, the handheld video monitor on the HIVE 2.0 has a custom 2-meter (6.56 foot) antenna extension cable. Lowering the antenna on the extension cable into the DI to the appropriate height can maintain line of sight for communication with the vehicle. This implements the principle described in Figure 30. There is a possibility of extending the reach of the antenna further with a longer SMA extension cable. This option remains untested.



(a)

(b)

(c)

Figure 62 (a) Simplified aerial view of VTrans Culverts 161158 and 161150 near U.S. Route 7 in Ferrisburgh, Vermont. Three inspection routes are shown. In "Path A" the inspection vehicle enters through the culvert outlet. In "Path B" the vehicle enters the left leg through the central drop inlet. In "Path C" the vehicle enters the top leg through the central drop inlet. Note the indirect route required to access Path C. (b) Photograph of culvert outlet. (c) Photograph of central drop inlet.

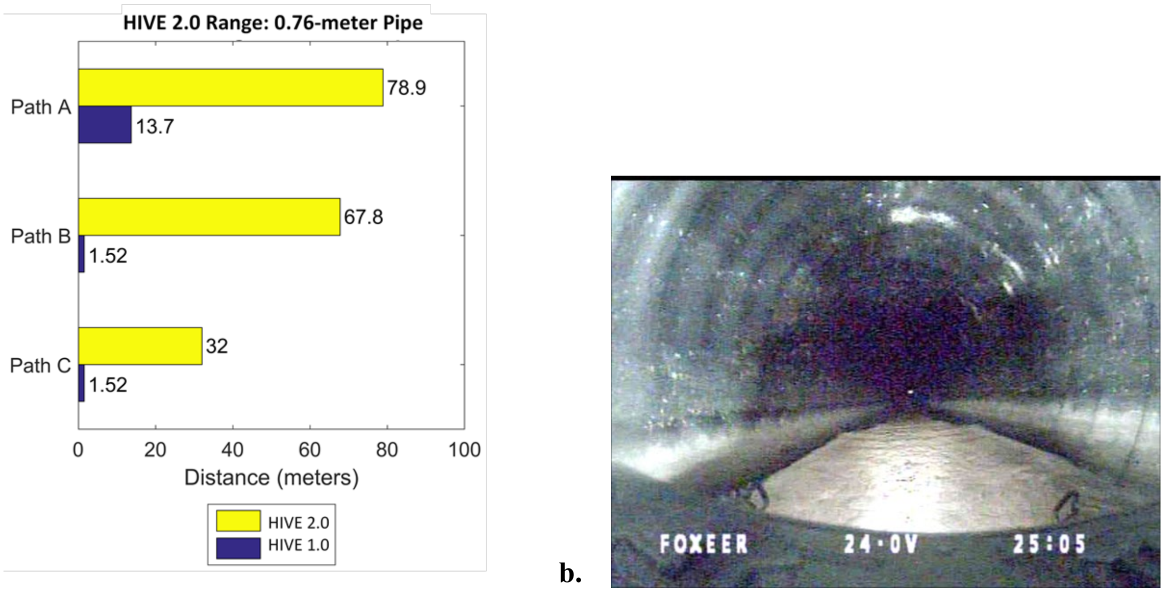
Figure 63 Antenna on extension cable and reflector dish inserted through drop inlet utility hole into telemetry beam line projecting from culvert

Figure 64 Insertion of video telemetry antenna on extension cable and reflector antenna into drop inlet through utility hole

Figure 65 HIVE 2.0 tank at entrance of culvert through drop inlet

Tests measured the functional RC and video telemetry range for the original HIVE 1.0 and HIVE 2.0 in the three paths denoted A, B and C in Figure 62.a. Path A drives the HIVE into the culvert via the outlet, while the operator stands at the outlet. Path A is straight with no DI or line-of-sight disruption. Path B drives the HIVE into the left culvert leg via the central DI. The DI geometry introduces a single line-of-sight disruption when the operator and telemetry instruments stand above ground. Dropping the antenna into the DI with an extension cable minimizes this disruption. The geometry of Path C is more challenging. There is a double bend between the operator standing at the central drop inlet and the top culvert leg. Using an antenna extension cable mitigates, but does not completely remediate, the losses due to the double bend in Path C.

Figure 66 shows the results of Telemetry Option Test 8. The HIVE 2.0 traversed the entire length of Path A and maintained operational video telemetry, a length of 78.9 meters (259 feet). The HIVE 1.0 was able to move along Path A for the significantly shorter distance of 13.7 meters (45 feet). Along the more challenging Path B through the DI the HIVE 2.0 traversed 67.8 meters (223 feet) while providing functional telemetry. The original HIVE 1.0 only functioned 1.52 meters (5 feet) on Path B. Path C with the double bend was most challenging. The HIVE 2.0 attained 32 meters (105 feet) of functional telemetry range. Figure 66.b shows a single video frame captured by the HIVE 2.0 and recorded on the operator's monitor during an inspection of Path C. The culvert is carrying several inches of flowing water but is otherwise unobstructed.



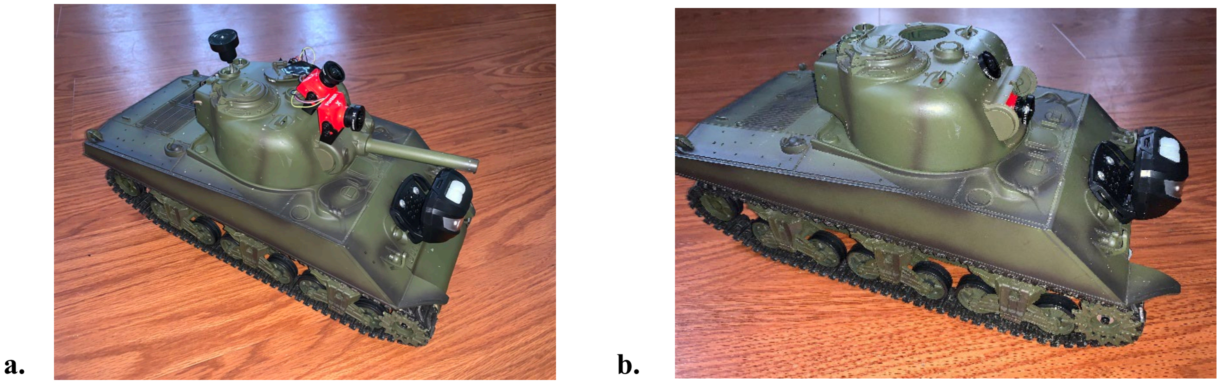
a.

b.

Figure 66 Results of Telemetry Option Test 8 evaluation of range extension by antenna on extension cable and reflector dish: a. Range comparison of HIVE 2.0 and HIVE 1.0, and b. A single frame from a HIVE 2.0 inspection video streamed to the operator's monitor. Here, the HIVE 2.0 traverses the culvert with several inches of flowing water while taking Path C.

3.9 Selected Camera and Telemetry Options

The HIVE 2.0 uses the chassis of an RC tank to transport the video transmission system into the culverts. The system uses two Foxeer Falkor cameras to transmit images from 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. They provide ease of installation, come in a robust case with custom mounting hardware, and affordable cost, Figure 33. The Sherman tank replica has a turret with 360-degree azimuthal rotation capability. The turret can turn the cameras from side to side. This built in functionality replaces servo motors used on HIVE 1.0. The turret is also a convenient housing to shield the cameras from damage. However, the tank gun barrel is only capable of providing 15 degrees of vertical elevation rotation, which is not enough to inspect a culvert fully with a single camera fixed to the barrel. To avoid adding a servo motor to extend vertical range of motion of motion, a second Foxeer Falkor camera aims with a 60 degrees elevation above horizontal to provide a complete view of the culvert, Figure 67. These two cameras connect with wires through a relay to a single wireless transmitter on the tank. This setup allows for the user to press a button on the RC to switch between the two cameras. Reduced power consumption and extended battery life is an added benefit of using only one transmitter for the two cameras. Two high lumen, rechargeable lights mounted to the chassis of the HIVE 2.0 tank provide illumination inside the culvert.



a. b.

Figure 67 Dual camera configuration with forward looking and 60 degree elevation upward looking cameras in turret: a. External mount for prototyping, and b. Internal mount in final design

The video transmitter, a Wolfwhoop Q4-DVR 5.8 GHz, has built in DVR capability that saves to a TF card. Omni- directional antennas on the transmitter and receiver enable video reception independent of antenna orientation. The user can choose to monitor the video through a 5.8 GHz monitor, or a 5.8 GHz receiver connected to an iOS or Android device. Both options allow for the video to be recorded and saved to the monitoring device. Multiple receivers can view the video transmission simultaneously. As presently configured, the system displays the video on a monitor.

Remote switching of the camera video channels requires either an upgrade or modification of the stock RC controller provided with the tank. Due to issues of simplicity, the decision was to upgrade the controller to a model that included remote relay control as a feature, the RadioLink AT10 controller with a modestly priced R12DS receiver/relay controller, Figure 69. This upgraded RC controller seemed to provide longer RC range than the stock controller. This perceived extended RC range was not quantified, primarily because the video telemetry range was usually the telemetry range constraint of the system and not the RC range.

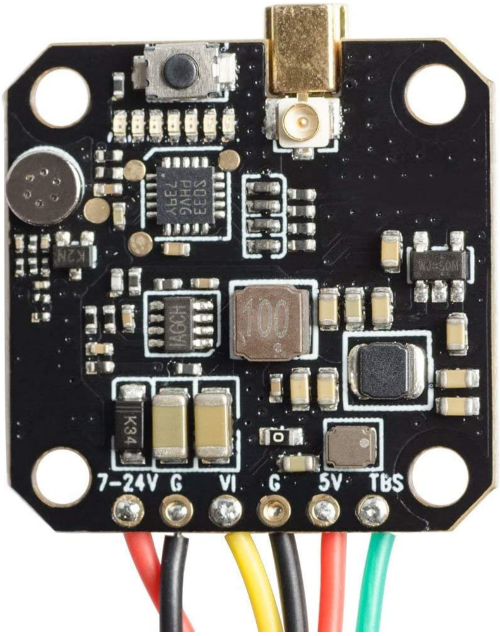


Figure 68 Wolfwhoop Q4-DVR 5.8 GHz, video telemetry transmitter with DVR capability that saves to a TF card

Figure 69 Selected remote control telemetry system: a. RadioLink AT10 controller, and b. RadioLink R12DS receiver/relay controller

4. Hydraulic Inspection Vehicle 2.0 (HIVE 2.0) Fabrication Details

4.1 Introduction

This section describes how to fabricate a Hydraulic Inspection Vehicle Explorer 2.0 (HIVE 2.0). The HIVE 2.0 design follows in many respects from the HIVE 1.0 previously designed and used by VTrans, and derived from a MnDOT design [Griffin 2019, Coughlin 2016]. The primary distinction between the HIVE 2.0 and the HIVE 1.0 is the choice of vehicle chassis. The HIVE 1.0 used an RC car from Traxxas as the chassis. The HIVE 2.0 uses an RC Sherman tank replica from Heng Long as the chassis. The HIVE 2.0 also uses lightweight video cameras and associated wireless telemetry on a 5.8 GHz band with in-culvert ranges that exceed those available on the HIVE 1.0.

4.2 Parts, Supplies and Tools

The first step is to acquire the necessary parts, supplies and tools required to assemble a HIVE 2.0. as specified in Table 4 and Table 5. Appendix A provides details on the parts, costs in 2020 prices, and a list of potential suppliers.

Table 4 Parts, supplies and tools needed to assemble HIVE 2.0

Parts and Supplies
RC Tank, Sherman M4A3, 1/16
2 x Camera, Foxeer Falkor
Transmitter, Wolfwhoop Q4-DVR 5.8 GHz
2 x Headlamp
Fast curing epoxy
Urethane waterproofing spray
CorrosionX HD waterproofing spray
20 AWG wire
Shrink tubing
Short traction bolts

Table 5 Tools needed to assemble HIVE 2.0

Tools
Drill
Drill bit, 1/2”
Drill bit, 3/8”
Drill bit, 1/16”
Heat gun
Screw drivers – Philips and flathead
Razor blade

4.3 ASSEMBLY STEPS

4.3.1 Step 1: Remove Unnecessary Hardware

Remove the speaker and smoke generator from the tank to simplify the waterproofing process and make more room for the relay device. First, remove the four screws holding the top and bottom half of the tank together must be removed. These screws are accessible on the bottom side of the tank, down deep bores. Once the top is free, place it aside without disconnecting the wires still tied to the bottom half of the tank. Unscrew the speaker and smoke generator and remove them while disconnecting their wires from the circuit board as shown in Figure 70.

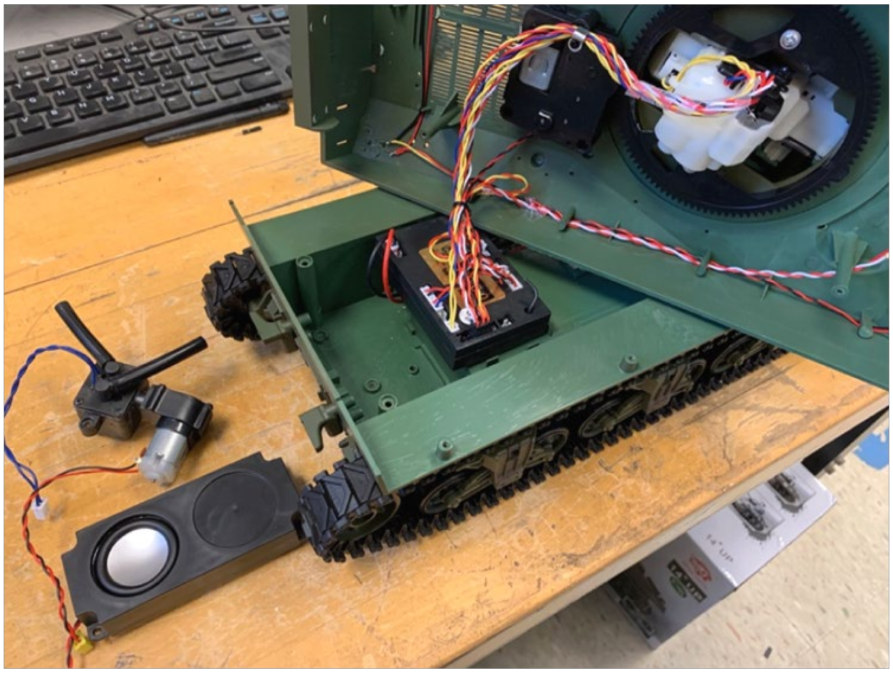


Figure 70 Tank with speaker and smoke generator removed

Remove the gun from the turret of the tank. Start by unscrewing the 2 screws in the large black ring gear as shown in Figure 71.

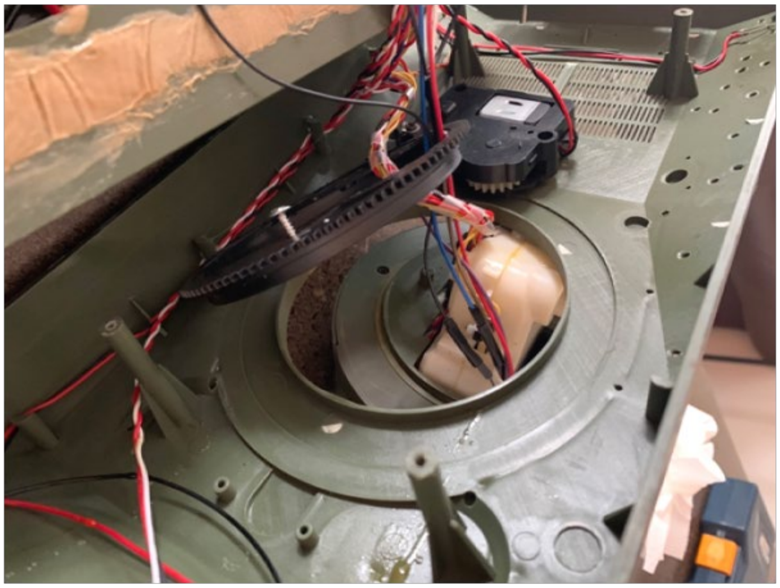


Figure 71 Black ring gear removed

Remove the 6 screws on the bottom of the turret. Looking at the exposed gun components with the barrel facing up, 2 silver screws are easily visible, securing the gear box on the left. Remove these two screws. There is still a third screw between the gear box and the main gun body securing this gear box. Force the main gun body to the right, away from the gear box to unscrew this third screw. Remove the gear box as shown in Figure 72.

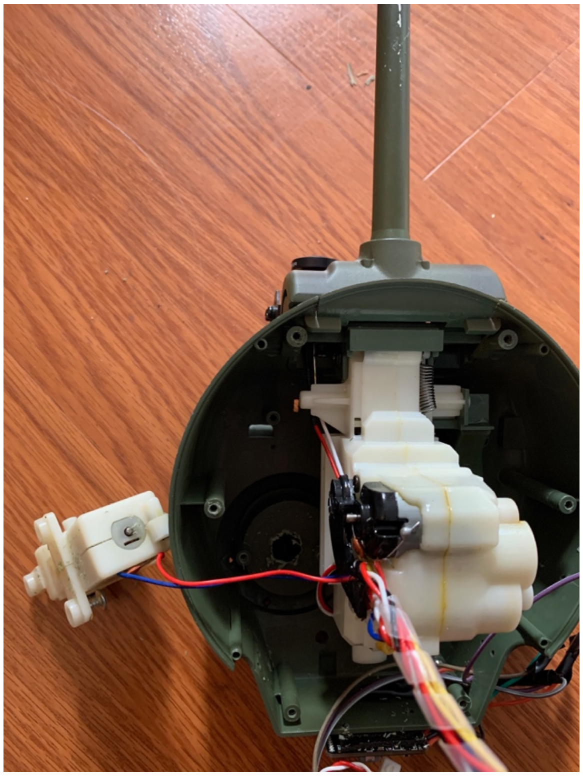


Figure 72 Gear box removed

To the right of the turret there are 3 screws securing the green BB holder. Unfasten the screws and remove the BB holder as shown in Figure 73.

Figure 73 BB holder removed

Unfasten the two screws at the front of the gun assembly facing in the direction of the barrel as shown by the blue arrows in Figure 74. Once removed, use pliers to break the plastic connecting the gun assembly to the turret shell as shown in red in Figure 74. Remove the gun.

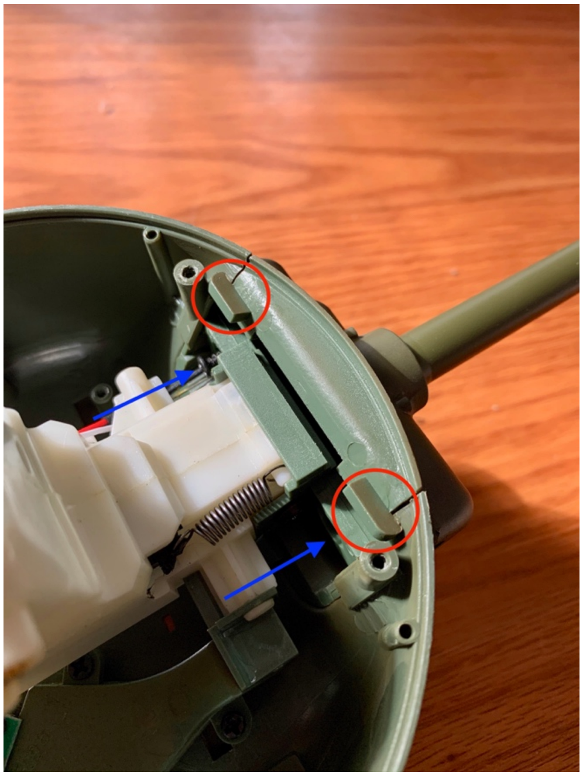


Figure 74 Gun front screws and plastic connectors

4.3.2 Step 2: Cut Holes Water Passage Holes in Chassis

Use the Dremel tool, knife and drill to cut water passage holes in the tank chassis as shown in Figure 13 and Figure 14.

4.3.3 Step 3: Mount Camera 1

Mounting the top camera requires drilling a hole through the turret shell. Start by drilling a pilot hole through the turret shell to locate the position and angle of the top camera. If the stock hole, as shown circled in red in Figure 75, is in the desired position, it can serve as the pilot hole. The stock hole produces a camera elevation angle of about 60 degrees which is recommended. Drill out the pilot hole with a 1/2-inch drill bit. Note that Figure 76 shows the 1/2-inch hole drilled in a pilot hole below the stock hole for a camera elevation angle of about 45 degrees.

Figure 75 Stock hole for Camera 1 position

Figure 76 1/2-inch hole drilled for Camera 1 mounting

Remove Foxeer camera from shipping box and fasten the mounting bracket to the camera using the middle position as shown in Figure 77. Unscrew the camera lens shaft from the body of the camera. Place the camera lens shaft through the 1/2-inch hole and screw it back onto the camera body.

Figure 77 Camera 1 bracket mounting position

Figure 78 Camera 1 position in turret

4.3.4 Step 4: Mount Camera 2

Mounting the second camera requires gluing the bracket of the camera to the base of the turret, with a strong adhesive, such as fast curing epoxy. Bond the bracket to the turret as shown in Figure 79. Be sure to position the bracket so that the corners of the bracket touch the inner diameter of the turret base. If the bracket is mounted too far out on the diameter, the cover will not fit in the following steps. Also be sure to orient the bracket as shown in Figure 79 to allow for adjusting the camera elevation angle downward as desired. Once the epoxy has cured, mount the camera to the bracket with the four provided screws and washers. The screws should be manually tightened to that the camera can pivot for elevation angle adjustment.

Figure 79 Camera 2 bracket position

Modify the turret cover as shown in Figure 80 and Figure 81 to fit in place to shield the camera. Remove the connectors on the back side. Use a pair of needle nose pliers to make the rough modifications. A razor blade, X-Acto knife or Dremel tool can make more precise cuts.

Figure 80 Camera 2 cover with plastic connectors removed

Figure 81 Camera 2 cover with cut made for camera

Use epoxy to bond the Camera 2 cover to the turret shell as shown in Figure 82.

Figure 82 Camera 2 cover bonded to turret shell

Screw the turret base plate under the turret shell as shown in Figure 83.

Figure 83 Camera 2 position in turret

4.3.5 Step 5: Mount Transmitter to Back of Turret

Place the transmitter in the location shown in Figure 84 and drill four pilot holes in the turret shell in locations matching the four holes in the transmitter. Screw the transmitter to the back of the turret. Drill a 3/8 inch hole for the wires to enter into the turret shell as shown in Figure 84. Mount the transmitter onto the back of the turret, Figure 85. Drill another 1/4 inch hole as shown in green and a 1/2 inch hole as shown in blue in Figure 86. These holes guide the positioning of the antenna.

Figure 84 Transmitter screwed to back of turret

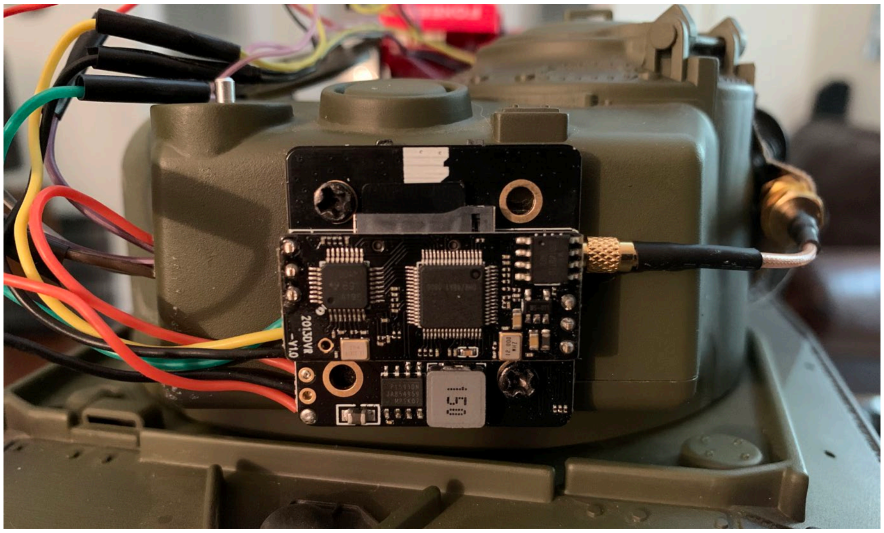


Figure 85 Transmitter board attached to back side of turret in assembled HIVE 2.0 tank

Figure 86 Holes drilled for antenna

4.3.6 Step 6: Mount Lights on Tank

Remove the hatch door on the turret as shown in Figure 87. This can be done easily with a pair of needle nose pliers. Sand the surface flat it before mounting the light.

Figure 87 Hatch door removed and partially protruding antenna mount

Position and attach the headlamp and mini flashlight by drilling pilot holes and screwing into position as shown in Figure 88.

Figure 88 Fully assembled HIVE 2.0

4.3.7 Step 7: Wire the Electrical Components

Remove the case of the circuit board to prepare for wiring and waterproofing. A flathead screwdriver can be used to pry the case apart. Once the bottom half is removed, unplug the cables to release the top half and then plug them back in. Care must be taken to return the cables to the original location.

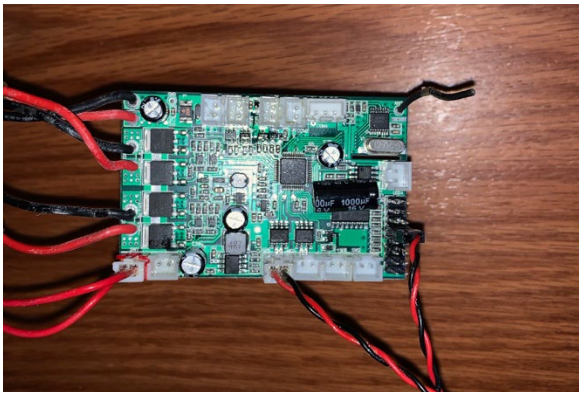


Figure 89 Circuit board with case removed

Wire the electrical components as shown in the Figure 90 wiring diagram. When connecting wires, be sure to use solder and shrink tubing. The wires connected to the circuit board of the tank should also be soldered. When connecting wires to the relay device, secure the wires by tightening the screws on the top. When wiring is complete, assembly the turret back onto the top half of the tank. Be sure to position the black ring gear so that the block in the teeth faces forward.

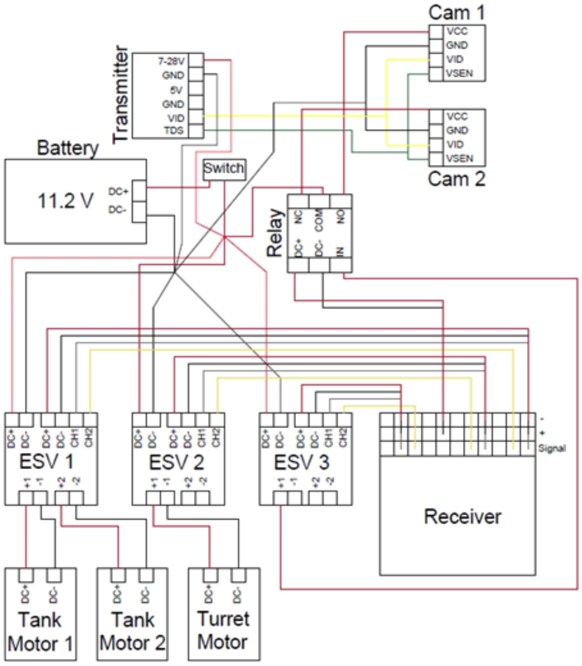


Figure 90 HIVE 2.0 wiring diagram

4.3.8 Step 8: Replace Tank Battery

The original tank battery is not capable of simultaneously powering the transmitter and tank especially when the battery life is diminished. A workaround is to replace the original battery with a more capable equivalent, a Gens ace 11.1V 1300mAh 3S 25C/50C LiPo Battery Pack with JST Plug for RC. Installation requires cutting off the connector of the original tank battery and wiring it onto the Gens ace battery. The original battery cable should be cut so that about 51 mm (2 inches) of wire remains off the connector. Cut the cable of the Gens ace battery right next to the connector to leave the maximum amount of cable. Strip and then solder together both battery cables and then wrap the splice in electrical tape as shown in Figure 91.

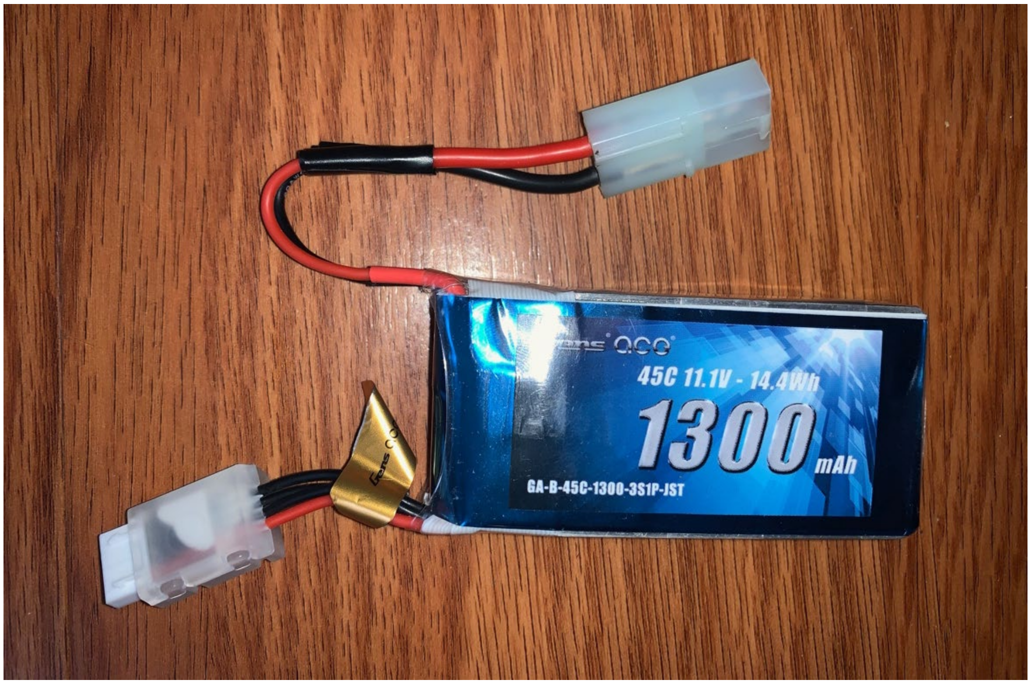


Figure 91 Battery replacement with new connector

4.3.9 Step 9: Waterproof Electronics

Waterproofing of the HIVE 2.0 tank electronics uses two coats of waterproofing spray. The first cost is CorrosionX HD which is a nonconductive spray that sets into a solid. The second is CRC Seal Coat which is a nonconductive urethane spray which sprays on as a viscous oil. Both products pose potential severe health risks and should be used with care. Be sure to read the safety data sheets and proceed according to their instruction. Use goggles, gloves, an appropriate mask, and only spray in a well-ventilated area such as a fume hood or a safe area outside.

Spray the circuit board, relay device, motor electrical leads, tank headlights and tank taillights with the CorrosionX HD. Spray generously on the circuit board, relay device, tank headlights, and tank taillights. When coating the electrical leads of the motors, be careful to not spray the moving parts since the coating will harden and may prohibit parts from moving. Now, using a small brush, spray the product into a small dish and brush a coating onto the leads of the On/Off switch on the bottom of the tank. Be sure to cover the exposed leads but to not prevent the switch from moving after the coating has cured. Allow the coating to cure overnight.

Next, use the CRC Seal Coat to cover the same surfaces again to act as a second layer of protection. Be sure to not spray the On/Off switch of the tank since it will prevent the switch from working. Take time to orient the components or mask off components to contain the spray only to the area that needs the coating. This product is very messy and will make doing repairs or handling the tank messy if the spray is not applied carefully. The following figures show the first waterproofing attempt. This used excessive coating to ensure a proper seal so there would be no doubt in the application when testing the method. However, the excessive coatings resulted in the On/Off switch getting stuck and an extremely messy vehicle to work with. Also, after getting the On/Off switch unstuck, it eventually became so clogged with the CRC Seal Coat that it stopped functioning. Be sure to coat fully the necessary areas and to keep the coating off all other surfaces.

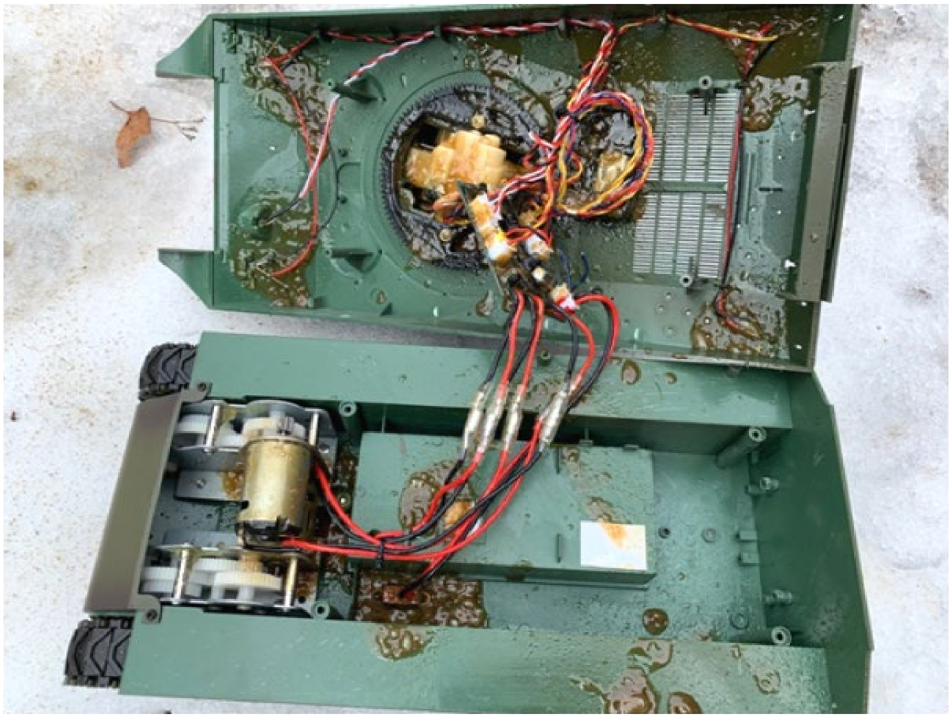


Figure 92. Tank waterproofing Photo 1

Figure 93. Tank waterproofing Photo 2

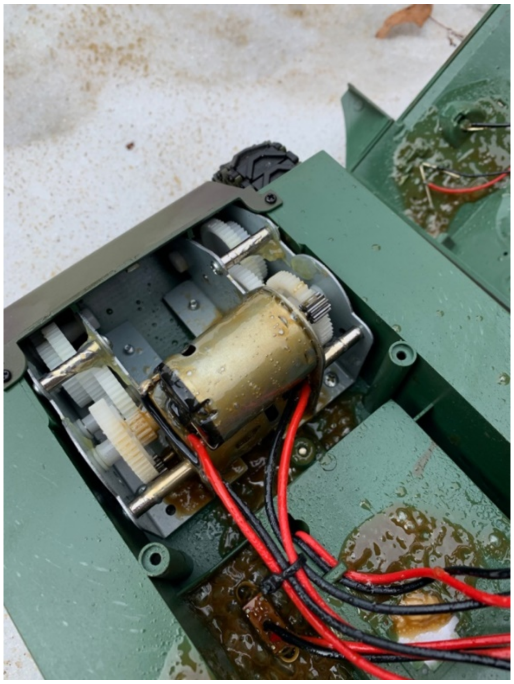


Figure 94. Tank waterproofing Photo 3

4.3.10 Step 10: Assemble Tank

Screw the top back on by reversing the steps in Step 1. The finished HIVE 2.0 appears in Figure 88.

5. CONCLUSIONS

The HIVE 2.0 culvert inspection vehicle described in this report meets all requirements specified by VTrans in in Table 2. Compared to the original HIVE 1.0, the HIVE 2.0 offers greater video range, improved capability to traverse obstacles, and more precise registration of distance traveled. The HIVE 2.0 design is affordable and easy to build. Table 6 reviews the engineering specifications which the HIVE 1.0 did not meet and shows where the HIVE 2.0 provides improvement.

Figure 88 shows the completed HIVE 2.0. A 1/16-scale Sherman M4A3 remote control tank meets the size requirements (Requirement 1), and features continuous tracks to facilitate clearance of separation gaps (Requirement 7) and position-holding on slopes (Requirement 9). Two high lumen, rechargeable lights are mounted to the chassis of the HIVE 2.0. A remotely controlled rotating turret pans two video cameras: one upward facing (60-degrees above horizontal), and one forward-facing. The video camera view is user-selectable via remote-control for increased inspection capability on a small, portable video screen. Foxeer Falkor cameras were selected based on a resolution of 1200 television lines (TVL), 155-degree field of view, and compatibility with a 5.8 GHz transmitter system. The cameras connect to the wireless transmitter through a wired relay connected to the receiver of the tank. The relay enables the operator to switch between the two cameras. Multiple 5.8 GHz video devices can view the video transmission simultaneously. The devices include a 5.8 GHz capable monitor, or a 5.8 GHz FUAV receiver connected to an iOS or android device. Both options allow recording the video. The transmitter on the HIVE 2.0 also has built in DVR capability that saves footage to a TF card. Omni-directional antennas provide good video telemetry performance even when the operator is not facing the HIVE 2.0. An optional improvement is to adhere small screws to the continuous tracks of the tank. This improves traction over obstacles such as rocks and branches. The total cost of HIVE 2.0 components is less than $1500.

A potential future line of effort would be to examine the extending video telemetry range of the HIVE 1.0 with an upgrade similar to that of the 5.8 GHz video telemetry system in the HIVE 2.0. The hardware is compact, lightweight and should fit with minimal modification to the HIVE

1.0 chassis. This could enable using the existing HIVE 1.0 fleet for more extended ranges in the inspection of culverts.

Table 6 Comparison of HIVE 2.0 capabilities versus original HIVE 1.0 for critical VTrans engineering specifications.

No.	VTrans Requirements	Engineering Specifications	HIVE 1.0	HIVE 2.0
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
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
9	Capable of stopping from rolling down hills	Vehicle shall remain still on 20-degree slope	Does not meet specification	Meets specification
11	User capable of knowing vehicle's location	User shall know vehicle's distance in culvert to+/- l' (305 mm) in culvert at all times	Moderately meets specification	Meets specification

REFERENCES

[Burton 2020] Burton JR. (2020) "Subsurface Sensing with Shakers and Inspection Vehicles" M.S. Thesis, Mechanical Engineering, University of Vermont

[Coughlin 2016] Coughlin M. (2016) "Hydraulics Inspection Vehicle Explorer" Minnesota Department of Transportation" http://www.dot.state.mn.us/research/projects/hive/CulvertVehicle.pdf

[Delogne 1991] Delogne P. (1991) "EM Propagation in Tunnels" IEEE Trans on Antennas and Propagation, 39, 3, 401-406, doi:10.1109/8.76340.

[Engan 2006] Engan (2006) "Waveguide Propagation." *Norwegian University of Science and Technology*

[Griffin 2019] Griffin J. (2019) "Vermont Agency of Transportation's Technical Transfer Adaptation of MnDOT's Hydraulic Inspection Vehicle Explorer (HIVE)" Transportation Review Board Annual Meeting 2019, paper no. 19-04998, Washington, DC

[Langlie 2016] Langlie K. (2016) "MnDOT's New Culvert Inspection Tool-The HIVE", AASHTO Committee on Hydrology and Hydraulics, Issue 13, 2016.

[Lehmann 2020] Lehmann M, McCabe M, Lewis M, Richards D. (2020) "Evaluation of New or Emerging Remote Inspection Technologies for Conduits Ranging from 12" to 120" Spans" Ohio Department of Transportation Report No. FHWA/OH-2020-5, Columbus, OH, 43223

[Losi 2020] http://www.losi.com/Products/Default.aspx?ProdID=LOS03004

[Rossow 2012] Rossow MP. (2012) "FHWA Bridge Inspectors Manual - Primer on Culverts" PDH Online, 5272 Meadow Estates Dr. Fairfax, VA 22030-6658

[Russer 2006] Russer P. (2006) "Electromagnetics, Microwave Circuit and Antenna Design for Communications Engineering" Artech House.

[Youngblood 2017] Youngblood D. (2017) "Enhanced Culvert Inspections - Best Practices Guidebook." Minnesota Department of Transportation, pp. 25-27.

APPENDIX A. PARTS LIST

Table 7 lists the parts, quantities and prices needed to assemble a HIVE 2.0. The date of these prices is August 2020.

Table 7 Parts needed to assemble HIVE 2.0

No.	Part Name	Website	Qty.	Units	Price/ Quantity ($)	Price ($) (August 2020)	Purpose
1	RC Tank	Amazon1	1	Each	308.09	308.09	Tank
2	Alternative	Amazon2	0	Each	249.99	-	Alt. Tank With Metal Upgrade
3	Compact Flashlight	Amazon3	1	Each	49.95	49.95	Front light
4	Headlamp	Amazon4	1	Each	13.99	13.99	Rear light
5	Screw, 4-40, 1/8"	McMaster1	2	100/pkg	8.42	16.84	Studs for Tank Tracks
6	Epoxy	McMaster2	1	Each	6.05	6.05	Attaching Studs to Tracks and General Glue
7	Urethane Waterproofing Spray	Amazon5	1	Each	12.99	12.99	Tank Waterproofing
8	Corrosion X HD	Amazon6	1	Each	22.53	22.53	Tank Waterproofing
9	5.8 GHz Monitor	Amazon7	1	Each	159.99	159.99	Video Monitor
10	Monitor Mount	Amazon8	1	Each	12.79	12.79	Mount Monitor to Tank Controller
11	Alternative	Amazon9	0	Each	12.95	-	Mount Monitor to Tank Controller
12	Revolution Counter	Amazon10	1	Each	12.49	12.49	Track Tank Distance
13	SMA Cables - 5ft	Amazon11	2	Each	7.99	15.98	Extend Antennas Into Drop Inlet
14	Circular Antennas	Amazon12	1	2/pkg	9.99	9.99	Replace Dipole Antennas

15	Transmitter Antenna	Amazon13	1	2/pkg	17.99	17.99	Antenna for Video Transmitter on Tank
16	Camera	Amazon14	2	Each	44.99	89.98	Camera
17	Transmitter	Amazon15	1	Each	23.99	23.99	Transmit Video from Tank Cameras
18	Alternative	Amazon16	0	Each	22.99	-	Alternative Source
19	Battery	Traxxas1	1	Each	39.99	39.99	Tank Battery
20	Reel	Amazon17	1	Each	24.29	24.29	Hold Steel Cable for Tank Retrieval
21	Loop Clamp 5/8"	McMaster3	1	25/pkg	6.91	6.91	Mount Revolution Counter Electronics Box to Reel
22	Loop Clamp 1/2"	McMaster4	1	25/pkg	6.14	6.14	Mount Revolution Counter Sensor to Reel
23	Bolt - 1/4"	McMaster5	1	100/pkg	5.51	5.51	Mount Revolution Counter
24	Nut - 1/4"	McMaster6	1	100/pkg	3.03	3.03	Mount Revolution Counter
25	Washer - 1/4"	McMaster7	1	100/pkg	3.47	3.47	Mount Revolution Counter
26	Controller	Amazon18	1	Each	158.99	158.99	Control Tank
27	Battery Adapter	Amazon19	1	3/pkg	10.68	10.68	Allow Traxxas Battery to Work With Tank
28	1/32" or 1 mm Wire Rope (500 ft)	Amazon20	1	Each	51.23	51.23	Cable for Tank Retrieval
29	1/32" Wire Thimbles	McMaster8	1	10/pkg	4.26	4.26	Prevent Cable Loop From Fraying

30	1/32" Wire Sleeves	McMaster9	1	50/pkg	2.45	2.45	Prevent Cable Loop From Fraying
31	Carabiner	Amazon21	1	4/pkg	10.99	10.99	Attach Cable to Tank
32	Relay Module	Amazon22	1	2/pkg	5.79	5.79	Switch Cameras
33	ESC Board	Amazon23	1	4/pkg	38.99	8.99	Control Tank Motors
34	Micro SD Card	Amazon24	1	Each	8.49	8.49	Store Video from Cameras
35	Satellite Dish	Amazon25	1	Each	49.95	49.95	Reflect Video and Controller Signals at Drop Inlets to Extend Range
	Total					**$1,174.80**	

The following is a list of detailed internet links as referenced in Table 7.

Amazon1: https://www.amazon.com/Rosvola-Control-Simulation-Sherman-Children/dp/B0834Q9HYB/ref=sr_1_2?dchild=1&keywords=Rosvola+3898-1+1%2F16+Scale&qid=1602085061&sr=8-2

Amazon2: https://www.amazon.com/Modified-Control-360-Degree-Rotating-Sprocket/dp/B07BFGT9P5/ref=sr_1_2?dchild=1&keywords=1%2F16+tank+rc+sherman&qid=1602114696&sr=8-2

Amazon3: https://www.amazon.com/Compact-Rechargeable-Flashlight-EdisonBright-charging/dp/B077ZJ2Y5T/ref=sr_1_6?dchild=1&keywords=olight+s1+mini&qid=1602109654&sr=8-6

Amazon4: https://www.amazon.com/Rechargeable-Headlamp-Lightweight-Waterproof-Adjustable/dp/B07D587F5D/ref=sr_1_1_sspa?dchild=1&keywords=goforwild%2Bheadlamp&qid=1605887910&sr=8-1-spons&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUFBRlRUNklaU1laRkEmZW5jcnlwdGVkSWQ9QTA4NzYwNTIyT0Q2QjdaQkpVVEVSJmVuY3J5cHRlZEFkSWQ9QTAzNzUzMjdJUVRWR0hUOUdFVEomd2lkZ2V0TmFtZT1zcF9hdGYmYWN0aW9uPWNsaWNrUmVkaXJlY3QmZG9Ob3RMb2dDbGljaz10cnVl&th=1

Amazon5: https://www.amazon.com/CRC-Urethane-Viscous-Coating-Temperature/dp/B000IC7ZQ2/ref=sr_1_3?keywords=electronic+waterproofing+spray&qid=1577074549&sr=8-3

Amazon6: https://www.amazon.com/Corrosion-X-90104-Heavy-Duty-12-Ounce-Aerosol/dp/B0009H1AMG/ref=sr_1_2?dchild=1&keywords=corrosion+x+hd&qid=1585178825&sr=8-2

Amazon7: https://www.amazon.com/Flysight-Diversity-Receiver-Sunshade-Airplane/dp/B07GBNQSJR/ref=sr_1_2?keywords=5.8+GHz+monitor+with+dvr&qid=1577073044&sr=8-2

Amazon8: https://www.amazon.com/Accessories-Aluminum-Monitor-Bracket-Transmitters/dp/B089ZFYH6Q/ref=sr_1_5?dchild=1&keywords=fpv%2Bmonitor%2Bmount&qid=1602091157&sr=8-5&th=1

Amazon9: https://www.amazon.com/FPV-Monitor-Screen-Mount-Universal/dp/B08LV4XK4R/ref=sr_1_2?dchild=1&keywords=fpv+controller+monitor+mount&qid=1605663417&sr=8-2

Amazon10: https://www.amazon.com/DIGITEN-Digital-0-99999-Proximity-Magnetic/dp/B01DNLRAUA/ref=sr_1_13?keywords=Electronic+Counter&qid=1584555097&sr=8-13&swrs=2D74BE0E5F3C02CBCBFCD3F23AE47FCB

Amazon11: https://www.amazon.com/ANHAN-Low-Loss-Extension-Connector-Pigtail/dp/B078W5JQZH/ref=sr_1_6_sspa?keywords=sma+cable+5+ft+same+male+to+female&qid=1577074427&smid=A39VJE6TACVRRU&sr=8-6-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUExQUkxNTJWR0JEU1ROJmVuY3J5cHRlZElkPUEwODIzNzI1M1BUQlA3VzNKRVExVCZlbmNyeXB0ZWRBZElkPUEwMjkwNTU3M1NBSlE2UTVENjVETCZ3aWRnZXROYW1lPXNwX210ZiZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=

Amazon12: https://www.amazon.com/Wolfwhoop-Omnidirectional-Antenna-Multicopter-Set-SMA/dp/B074R9WRCV/ref=sr_1_15?dchild=1&keywords=5.8+video+sma+antenna&qid=1605661346&sr=8-15

Amazon13: https://www.amazon.com/iFlight-Antenna-Quadcopter-Multicopter-Purple/dp/B08926YDTK/ref=sr_1_4?dchild=1&keywords=MMCX+5.8+antenna&qid=1602112964&sr=8-4

Amazon14: https://www.amazon.com/FOXEER-Camera-Falkor-1200TVL-1-8mm/dp/B07G97JL5B/ref=pd_sbs_21_1/133-6838129-8042531?_encoding=UTF8&pd_rd_i=B07G97JL5B&pd_rd_r=f2b8de41-f42b-475c-80ea-37b1bacc57a4&pd_rd_w=rWx4D&pd_rd_wg=iej1P&pf_rd_p=bdd201df-734f-454e-883c-73b0d8ccd4c3&pf_rd_r=84AHAN8A1SW69FASJKRN&refRID=84AHAN8A1SW69FASJKRN&th=1

Amazon15: https://www.amazon.com/Wolfwhoop-Q4-DVR-5-8GHz-Switchable-Transmitter/dp/B07ZJKVVRH/ref=sr_1_2?keywords=5.8+ghz+transmitter+with+dvr&qid=1585179867&s=hi&sr=1-2

Amazon16: https://www.amazon.com/AKK-Support-Configuring-Betaflight-Control/dp/B07CG5P9B9/ref=sr_1_3?dchild=1&keywords=AKK+FX2+5.8Ghz+FPV+Transmitter&qid=1605889959&sr=8-3

Amazon17: https://www.amazon.com/Prime-CR003000-Portable-Metal-100-Ft/dp/B0017XOIJI/ref=sr_1_5?dchild=1&keywords=extension+cord+reel+stand&qid=1603476375&sr=8-5

Amazon18: https://www.amazon.com/Radiolink-Transmitter-Controller-Multicopters-Helicopter/dp/B07FPF2HQR/ref=sr_1_2?dchild=1&keywords=radiolink+at10&qid=1602090481&sr=8-2

Amazon19: https://www.amazon.com/OliYin-Traxxas-Adapter-Connector-Battery/dp/B07C6P56MR/ref=sr_1_7?dchild=1&keywords=Traxxas+Plug+Male+to+Tamiya+Head+Female&qid=1605660409&sr=8-7

Amazon20: https://www.amazon.com/Stainless-Steel-Aircraft-Cable-T304/dp/B00TYSAVBW/ref=sr_1_3?dchild=1&keywords=1%2F32+steel+cable+500&qid=1605662380&sr=8-3

Amazon21: https://www.amazon.com/Faswin-Stainless-Steel-Spring-Carabiner/dp/B01H1SK1SO/ref=sr_1_9?dchild=1&keywords=3+inch+stainless+steel+carabiner&qid=1605888920&sr=8-9

Amazon22: https://www.amazon.com/HiLetgo-Channel-optocoupler-Support-Trigger/dp/B00LW15A4W/ref=sr_1_5?dchild=1&keywords=relay+module&qid=1605750787&sr=8-5

Amazon23: https://www.amazon.com/FPVDrone-Brushed-Speed-Controller-Bidirectional/dp/B083WDRP24/ref=sr_1_2?dchild=1&keywords=Dual+Way+Bidirectional+Brushed+Esc&qid=1605750711&sr=8-2

Amazon24: https://www.amazon.com/SanDisk-Ultra-microSDXC-Memory-Adapter/dp/B073JWXGNT/ref=sr_1_4?dchild=1&keywords=32gb+micro+sd+card&qid=1605895314&sr=8-4

Amazon25: https://www.amazon.com/DIRECTV-060209-DirecTv-18-Inch-Satellite/dp/B000HRQXQQ/ref=sr_1_15?dchild=1&keywords=satellite+dish&qid=1605920429&sr=8-15

McMaster1: https://www.mcmaster.com/91781A103

McMaster2: https://www.mcmaster.com/7605A5

McMaster3: https://www.mcmaster.com/3225T5

McMaster4: https://www.mcmaster.com/3225T4

McMaster5: https://www.mcmaster.com/91309A540

McMaster6: https://www.mcmaster.com/90473A029

McMaster7: https://www.mcmaster.com/92141A029/

McMaster8: https://www.mcmaster.com/3436T12/

McMaster9: https://www.mcmaster.com/3897T31/

Traxxas1: https://traxxas.com/products/parts/2823X

Appendix B. Guidelines and Plan for Implementation

The HIVE 2.0 design described in this report is functional and ready for use in more extensive trials, followed by potential implementation in routine use for the inspection of culverts. The following is a set of suggested guidelines toward that end. This assumes that VTrans is in possession of a single prototype HIVE 2.0.

1. Acquire parts and build a second HIVE 2.0 according to procedure outline in Section 4. Choose the metal track option for comparison with the plastic track option used in the original prototype. It is estimated that it will take approximately 8 hours to assemble a single HIVE 2.0. In 2020 prices, the cost of parts for a single HIVE 2.0 including telemetry and viewing hardware is $1,175. The assembly is straightforward, but requires the ability to use hand tools, including those needed to assemble electronics.
2. Conduct field trials with the two HIVE 2.0s to establish long term durability. Identify parts that fail and other items and issues of concern.
3. Redesign and resource components of HIVE 2.0 as determined in the field trials.
4. If information from the field trials becomes available, select metal versus plastic treads for future fleet of HIVE 2.0s.
5. Acquire parts and fabricate fleet of HIVE 2.0s
6. Use HIVE 2.0s in the field for inspection of culverts. Identify any emergent technical issues and correct as needed.
7. Option: Implement telemetry upgrade from HIVE 2.0 on HIVE 1.0 fleet.