Remote Sensing Direct Measurement Mandrel for Use in Pipes

Division of Engineering Research On-Call Services Task 4

Prepared by Issam Khoury and Jay Wilhelm

Prepared for the Ohio Department of Transportation
Office of Statewide Planning and Research

March 2021

Final Report

Ohio Research Institute for
Transportation and the Environment

1. Report No. FHWA/OH-2021-08	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Remote Sensing Direct Measurement Mandrel for Use in Pipes Division of Engineering Research On-Call Services Task 4		**5. Report Date** March 2021
		6. Performing Organization Code
7. Author(s) Issam Khoury and Jay Wilhelm		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Ohio Research Institute for Transportation and the Environment (ORITE) 231 Stocker Center Ohio University Athens OH 45701-2979		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. Agreement No. 31796
12. Sponsoring Agency Name and Address Ohio Department of Transportation Office of Research and Development 1980 West Broad St. Columbus OH 43223		**13. Type of Report and Period Covered** Final Technical Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Ohio Department of Transportation (ODOT) and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The objective of this project was to develop a low-cost Remote Sensing Direct Measurement Mandrel (RSDMM) that can measure the internal in-situ diameter of buried flexible pipe with diameter ranging from 24 in (610 mm) to 48 in (1220 mm). This was achieved by modifying the ODOT Turtle Rover to include a LiDAR and forward-facing camera all controlled by an Arduino controller and a pi-top base station with an Xbox controller. The Turtle Rover was able to communicate to the pi-top via Wi-Fi connected through a provided Wi-Fi-dongle. Laboratory calibration on 24 in (610 mm) diameter HDPE pipe showed that the LiDAR provided had a resolution 0.039 inches (1mm) and a standard deviation of 0.14911 inches (3.78 mm) when measuring a 24-inch diameter HDPE pipe.

17. Key Words Pipe profiling, LiDAR,		**18. Distribution Statement** No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 21	**22. Price**

Remote Sensing Direct Measurement Mandrel for Use in Pipes

Division of Engineering Research On-Call Services Task 4

Prepared by

Issam Khoury and Jay Wilhelm

Ohio Research Institute for Transportation and the Environment
Russ College of Engineering and Technology
Ohio University
Athens, Ohio 45701-2979

Prepared in cooperation with the
Ohio Department of Transportation
and the
U.S. Department of Transportation, Federal Highway Administration

Final Report
March 2021

Acknowledgments

The authors would like to thank ODOT for their financial and administrative support as well as for their technical guidance of this project. We would like to acknowledge the contributions of Dr. Kevin White of EL Robinson as the overall Research-On-Call Services project manager. The ODOT Technical Advisory Committee for the project included Jeffrey Syar, Matthew Cozzoli, and Matthew Retta. Michelle Lucas of the Research Section handled project administration details at Central Office.

Contents

Figures

Tables

Project Background

ODOT CMS 611 specifies vertical deflection as a performance measure indicative of proper installation of flexible pipe. Manual deflection measurements are not easy in conduits less than 48 in (1220 mm) in diameter and are not possible in conduits with diameter less than 36 in (910 mm). Remote conduit measurement equipment is required to obtain interior dimensions on smaller diameter conduits where the vertical deflection needs to be determined.

Current commercially available remotely operated equipment does not provide a direct profile measurement of the conduit's interior, is expensive, and requires significant training. Available profile measurement equipment typically utilizes a combination of sensors such as an optical sensor (camera) that takes a picture of a projected laser ring and requires manipulation by a technician to obtain deformation measurements. Subjectivity is introduced into the measurement during the manual steps. The laser ring technology is also suspect when there is water in the conduit since the laser cannot differentiate between the water surface and the conduit interior and the laser light is refracted by the water. Direct measurement equipment such as that provided by a Light Detection and Ranging (LiDAR) (time of flight) photoelectric sensor or an ultrasonic sensor is preferred to remove the subjectivity from the measurement and to reduce the amount of operator training required.

In 2002, a direct measurement mandrel, shown in Figure 1, was developed by Ohio University to measure thermoplastic conduits for the study entitled *Field Verification of Structural Performance of Thermoplastic Pipe Under Deep Backfill Conditions* [Sargand et al., 2002]. The mandrel performed direct distance measurements using a laser at specified angles of rotation at a given longitudinal position. The longitudinal position is set by pulling the device with a tow line to the desired location. The laser device is attached to a rotating arm pivoting about a central axis. The arm is rotated by stepping a set angular increment (say 10°), at which point a distance measurement is made with the laser and recorded. The recorded radial distances and angles establish a circumferential profile of the pipe. The best available technology at the time was used, but it is now outdated. Today's available technology, such as inexpensive open-source electronic platforms (e.g. Raspberry Pi or Arduino) and improved sensors, make it possible to create a low-cost, compact system that will perform direct measurements suited to ODOT's needs.

Figure 1. Direct Measurement Mandrel developed in 2002 by Ohio University [Sargand et al., 2002].

Objective

The objective of this project is to develop a low-cost Remote Sensing Direct Measurement Mandrel (RSDMM) that can measure the internal diameter in situ of buried flexible pipe with diameter ranging from 15 in (380 mm) to 48 in (1220 mm) at the minimum following locations: 12 to 6 o'clock, 1:30 to 7:30 o'clock, 3 to 9 o'clock, and 4:30 to 10:30 o'clock.

The direct measurement remote sensors utilized may include but are not limited to ultrasonic or photoelectric with Class I laser. In addition, a retractable linear variable differential transformer (LVDT) may be included as an alternative technique for direct measurement of the conduit interior when water is present in the conduit. The device will include an electronic Inertial Measurement Unit (IMU) with an accelerometer, gyroscope, magnetometer, and altimeter, which could measure and record the X, Y, and Z displacement of the RSDMM (in particular the axis of rotation for the pipe profile measurements) relative to the initial starting point.

Implementation options include attaching the sensors to an already owned ODOT inspection crawler, e.g. ODOT HIVE or Turtle Rover, or mounting on a sled or wheeled chassis pulled longitudinally into place with a tether. The Office of Hydraulic Engineering (OHE) can provide support in terms of connecting or modeling 3D printed attachments for the RSDMM sensors if attachment to the ODOT HIVE or Turtle Rover is deemed applicable. All options will be vetted during development of the RSDMM.

Technical Requirements

The RSDMM must meet the following minimum requirements:

1. Ability to meet or exceed accuracy and precision requirements in accordance to ASTM F3080 -17a Section 9.1 and Section 9.2.
2. Ability to transmit collected data to a Windows or iOS device using WiFi and/or through a shielded, robust, and waterproof cable to a length of 400 ft (120 m). Ensure cables are attached to the RSDMM such that a tension load is not transferred directly to the electrical connection.

3. Ability to display real-time longitudinal distance from the initial starting point on a Windows or iOS device.
4. Visual camera with adequate lighting to determine where to take measurements. A pan and tilt system may be warranted.
5. Output a Microsoft Excel file with the means of interpreting the collected data that translates directly to pipe vertical deflection percentage and identification and quantification of non-uniform cross sections of the conduit as a function of longitudinal distance through the pipe

Method

To meet the objectives of this project the Ohio University team embarked on studying and comparing the various options available to it within the constraints of this project. The tasks to accomplish the objective of this project are listed below including pertinent data collected. Throughout this project, communication with the TAC was maintained via monthly calls with the TAC regarding progress as well as getting feedback from the TAC at other times, for example on the various components used.

Review of existing pipe profile characterization systems

Shape measurement of pipes using robots was discussed in two papers, one by K. Matsui [2010] and the other by K. Kawasue [2013]. Both papers discuss the use of mobile robot systems equipped with cameras interfaced with a computer vision system and a laser system that would paint the inside of the pipe to aid the camera vision system measure the inside pipe circumference. These systems rely on camera vision systems to measure the inside diameter of these pipes. This method was explored in the past by Ohio University ORITE in a custom fabricated system used for measuring the deflection in pipes in a coper mine in Chile [Sargand et al., 2016]. The system required extensive optical and mechanical calibration and would be cumbersome for use in routine field work.

Newer technology used by pipe inspection operators, include the use of Light Detection and Ranging (LiDAR) sensors in addition to cameras to measure pipe diameters. These LiDAR systems are usually attached to robots that can travel through pipe systems.

LiDAR uses a pulsed laser to calculate an objects distance from a fixed point, in this case the LiDAR itself. As the laser is rotated 360°, these laser measurements are added together to form an image of the inside of a pipe. These LiDAR systems can range in cost from tens of thousands of dollars to hundreds of dollars depending on the application and resolution required.

In addition to the LiDAR and camera system, a controller and interface system are necessary to provide feedback to the robot and operator. A cost-efficient controller and interface system can be developed using newer available technology such as Arduino and Raspberry Pi.

Telephone inquiries made to pipe inspection operators and pipe inspection robot manufacturers indicated that robot systems are very expensive to purchase ($100k or more) and are usually leased on a per pipe basis, which would make it prohibitively expensive for ODOT to own.

Therefore, it was decided that Ohio University would build a cost-effective pipe inspection robot for ODOT, using cost-efficient technologies as mentioned below.

Research on existing measurement systems and sensors

The Ohio University team researched the necessary components and system packaging methods to meet the evaluation requirements as developed during the start-up meeting. The research team met with manufacturers of single point laser measuring systems, manufacturers of high accuracy contact sensors, and Linear Variable Displacement Transducers (LVDTs). These systems proved to be either too expensive or too cumbersome to provide the necessary data required for this project.

LiDAR presented a cost-effective alternative. The team used its existing experience with distance sensors (LiDAR) to develop a plan to create a configuration that balances cost and performance and determined which technologies were the most viable for measuring and recording deflections and selected sensors accordingly.

The research team held a meeting with ODOT Office of Hydraulic Engineering (OHE) to demonstrate various sensor and equipment options available so OHE could make an informed decision on whether to select a configuration and continue with the project or to cancel it. The presentation included information on the relative accuracy, precision, and cost of each option. A list of supplies required with prices was drafted and presented for each configuration. OHE then picked the configuration to be developed further.

The measuring LiDAR that was chosen, the RPLIDAR S1 from Slamtec, has specifications as shown in Table 1 below.

Table 1. RPLIDAR Model S1 LiDAR Specifications

Item	Detail
Application Scenarios	Ideal for both outdoor and indoor environments with reliable resistance to daylight.
Distance Range	White object: 130 ft (40 m)
	Black object: 32 ft (10 m)
Blind Range	0.04 in (1 mm)
Sample Rate	9.2 kHz
Scan Rate	Typical value: 10 Hz (adjustable between 8 Hz-15 Hz)
Angular Resolution	Typical value: 0.391° (0.313°-0.587° depending on scan rate)
Communication Interface	TTL UART
Communication Speed	256,000 bps
Accuracy	±2 in (±50 mm)
Resolution	1.2 in (30 mm)

In addition to the LiDAR, the OHE Turtle Rover was modified to enable the attachment of a forward-viewing camera, LED lights, control boards, servo motors, and a Wi-Fi connection to allow for the remote operation and monitoring of the rover as specified in the task order. The complete list of components used is included in Appendix A.

Laboratory Prototype RSDMM Development

Based on the OHE-approved system and components list, the Ohio University team designed, procured parts for, and built a laboratory prototype of the proposed RSDMM. Figure 2 shows the system diagram concept for the control of the Turtle Robot including the LiDAR.

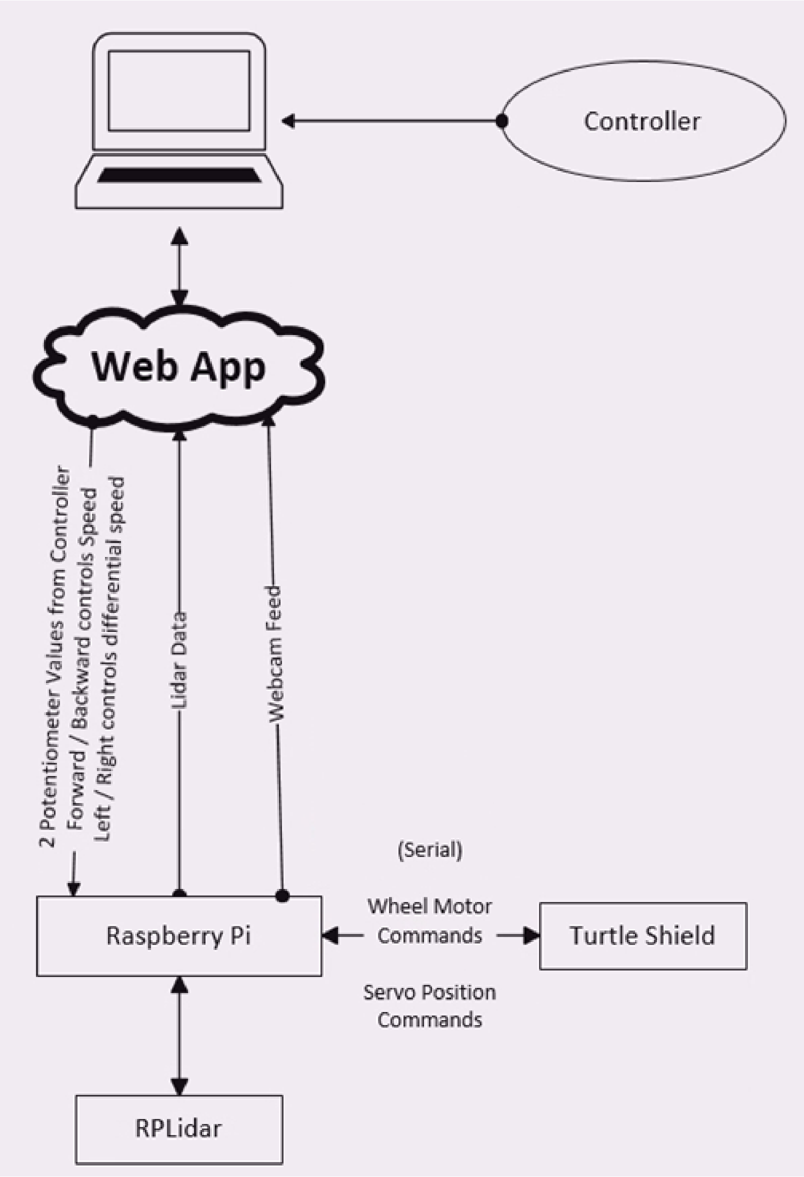

Figure 2 System Diagram Concept

The use of modular assembling materials and techniques reduced building time and allows for future expandability. A LiDAR mount was created using 3-D printed parts to assure modularity of the rover. Figure 3 shows the mounting bracket including the servo motor for side to side rotation. As shown in Figure 4, a custom enclosure was created to house the electronics controlling the rover and sensors. Open source software and firmware were used in the system and a document was created detailing the build process including detailed costs of each component and labor required for a completed RSDMM. The operating manual for the Turtle Rover is supplied to ODOT as a separate document.

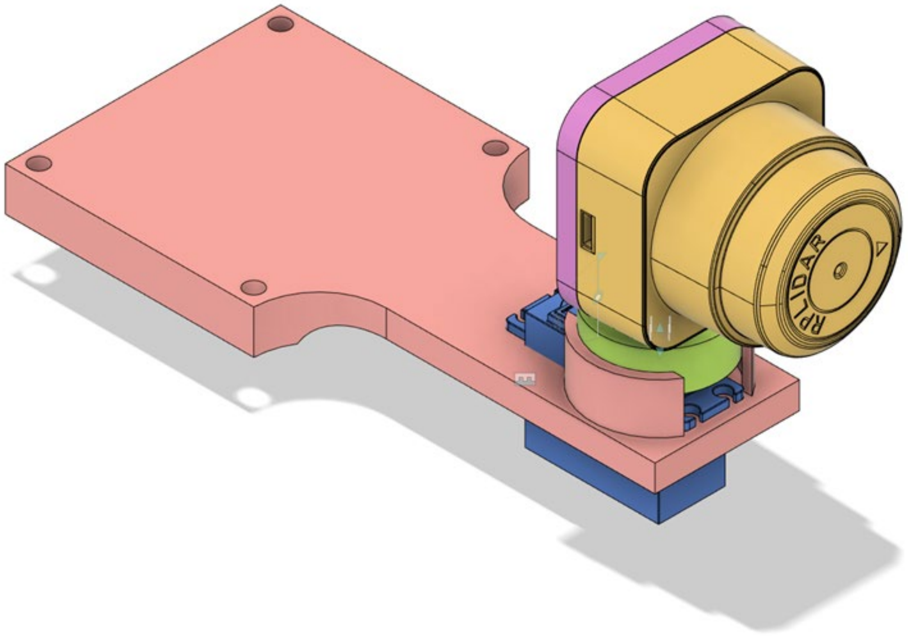

Figure 3 LiDAR Mounting Bracket

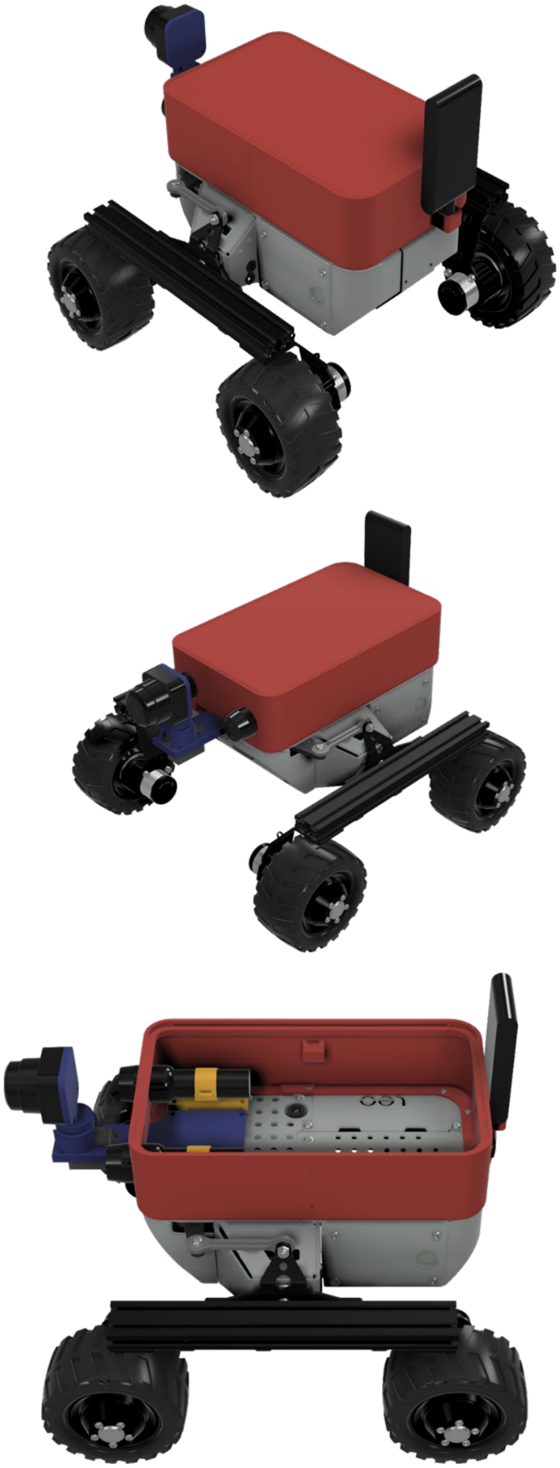

Figure 4 Custom Enclosure for the Turtle Rover

Figure 5 below shows the prototype Turtle Rover with the enclosure housing the camera system, LiDAR, lights, batteries, and USB hub. Figure 6 shows the pi-top base station used to communicate with the rover, and Figure 7 shows a schematic of the communication protocol used to control the rover.

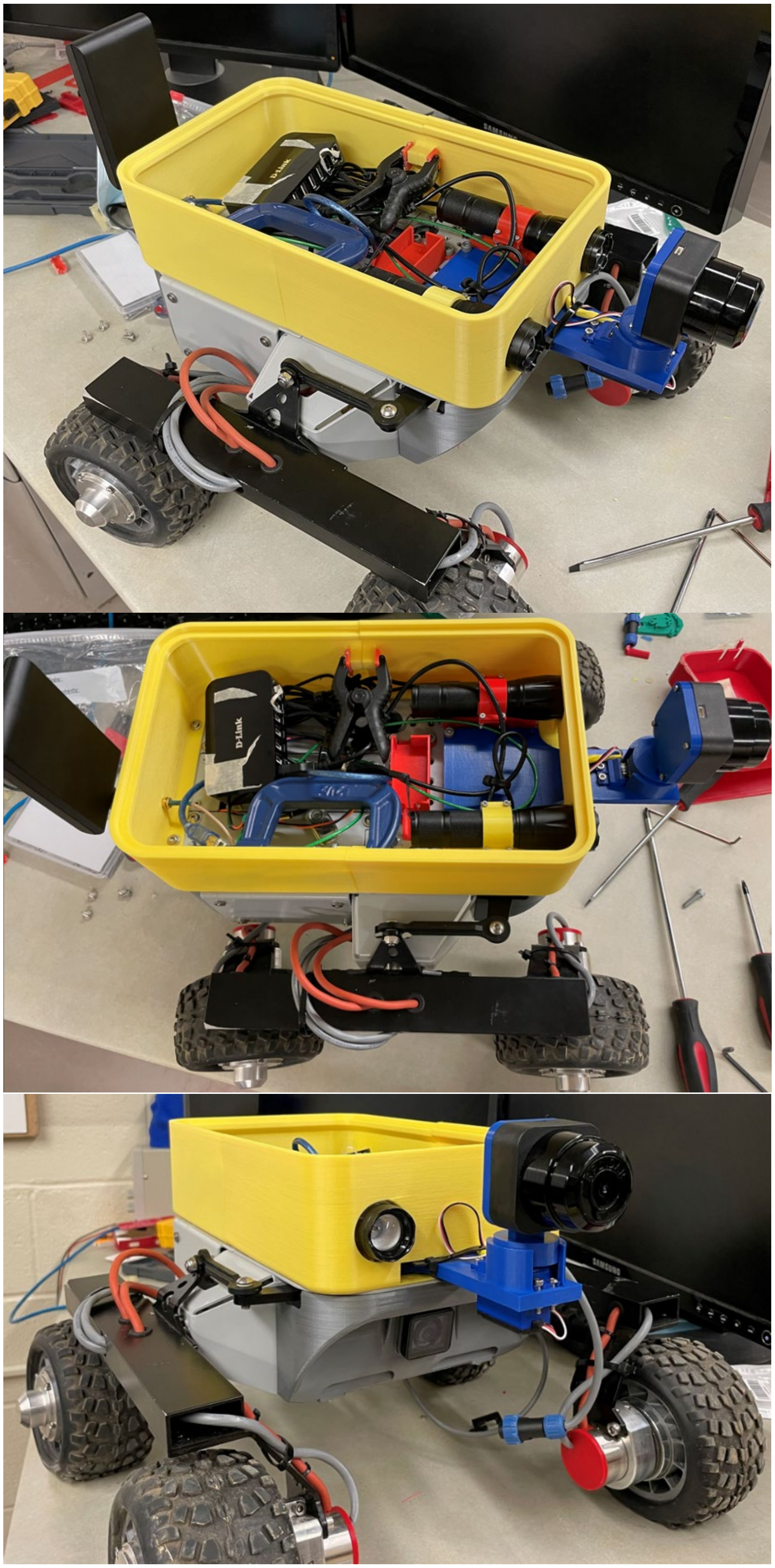

Figure 5 Prototype Turtle Rover

Figure 6 Pi-top base station

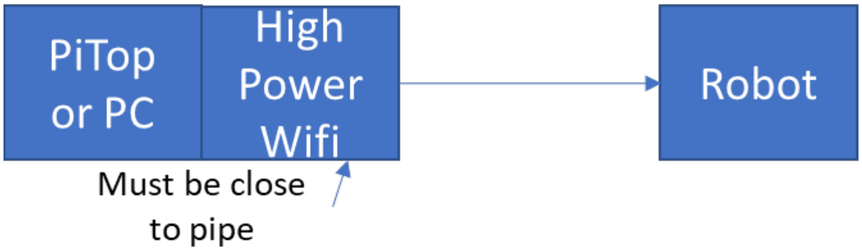

Figure 7 Communication Protocol

RSDMM Prototype Demonstration

The prototype RSDMM was demonstrated to OHE personnel who provided feedback on the design and software. As a result, the RSDMM was modified to include a shutdown button on the web interface, ensure that each value in the export data sheet was defined, and to show the equations used to determine each data column. The Turtle Rover manual includes a section for setting the date and time and troubleshooting guide.

Laboratory Evaluation of the RSDMM Prototype

Due to COVID-19 constraints and the inability of the research team to access a full range of various size pipes, the RSDMM was tested in a laboratory setting on a 24-in (610 mm) HDPE pipe. Once data collection is initiated, the LiDAR collects data at 0.4993° intervals corresponding to approximately 557 data points for each rotation. At a typical data collection location, The LiDAR rotates between 40 and 50 times to collect approximately 22,000 to 28,000 data points. For each of these data runs, a text file (.csv) is generated with header information as shown in Table 2 below. In addition to the text file, a photo is generated of the location for the data collection. This information is summarized in a report that is stored on the pi-top base station for later retrieval.

Table 2 Header Field Data Explanation

Header Field	Explanation
Angle [deg]	LiDAR Angle
Range [in]	Distance to Detected Object (in)
X [in]	Cartesian Conversions of the angle and range X (in)
Y [in]	Cartesian Conversions of the angle and range Y (in)
Time	Time data were collected
AvgR [in]	Average Radius (in)
StdR	Standard Deviation of the Radius (in)
minR [in]	Minimum Radius Measured (in)
maxR [in]	Maximum Radius Measured (in)
Odometer	Odometer reading at the location of the data
eulerX	Orientation angle of the robot along X axis [deg]
eulerY	Orientation angle of the robot along Y axis [deg]
eulerZ	Orientation angle of the robot along Z axis [deg]
gyroX	Gyroscope value in X axis at time of sample [deg/sec]
gyroY	Gyroscope value in Y axis at time of sample [deg/sec]
gyroZ	Gyroscope value in Z axis at time of sample [deg/sec]
accX	Accelerometer sample at time of sample in X axis [g]
accY	Accelerometer sample at time of sample in Y axis [g]
accZ	Accelerometer sample at time of sample in Z axis [g]
magX	Magnetometer sample at time of sample in X axis [deg]
magY	Magnetometer sample at time of sample in Y axis [deg]
magZ	Magnetometer sample at time of sample in Z axis [deg]
BatVolt	Battery Voltage (V)
lsq_center_x	Least Square Ellipse fit center x coordinate [in]
lsq_center_y	Least Square Ellipse fit center y coordinate [in]
lsq_width [in]	Least Square for the width of the Ellipse [in]
lsq_height [in]	Least Square for the height of the Ellipse [in]
lsq_phi	Least Square for the angle phi [degrees]

Note: g is the value of earth's gravitational acceleration, 32.17405 ft/s^2 (9.80665 m/s^2)

The calibration procedure listed below was used to calibrate the LiDAR in the lab using 24-in (610 mm) HDPE pipe.

- Place Turtle LiDAR in a pipe with known diameter. Alternatively, one can use a flat piece of black HDPE plastic placed at a known distance above the center of the LiDAR unit and a second piece of HDPE under the LiDAR unit at a known distance; the sum of the up and down distances represents the pipe diameter.

- Align the LiDAR unit to zero angle position with measured distance to object/pipe (demoted by triangle on top of LiDAR)
  - Make sure calibration object is horizontal.
  - The robot will move a servo to center the LiDAR vertically.
- Begin measurement procedure using the controller.
- Repeat process a number of times until reaching the desired accuracy of calibration.
- Download dataset as csv files.
- Isolate out zero angle (±0.2°) data points.
- Take average of all data points near or at zero degrees. This average is the measured diameter.
- Subtract known diameter from the measured diameter and use as calibration offset.
- Apply the calibration offset to all readings when post processing ranges from downloaded files.

Table 3 shows an example based on data collected at Ohio University's laboratory.

Table 3 Example Calibration Data

```
Measured average diameter in inches
25.028859283291332
25.03331307738526
Average measured diameter in inches
(25.028859283291332 + 25.03331307738526)/2 = 25.031086180338296
The known pipe diameter is 23.75 inches
The calibration offset is:
25.031086180338296 - 23.75 = 1.2810861803382956 inches
```

Enough measurements were compiled in the laboratory tests to ensure that the precision and repeatability requirements were achieved. The data were analyzed to ascertain the robustness, repeatability, precision, of the RSDMM. From the data analysis conducted, the LiDAR resolution was calculated to be 0.039 in (1 mm).

Figure 8 through Figure 13 show the data collected to calibrate the LiDAR in the lab. The Ellipse fit in each figure shows the best fit of an ellipse which falls within the constraints of the pipe used. The average standard deviation of the radius was calculated to be 0.14911 in (3.79 mm).

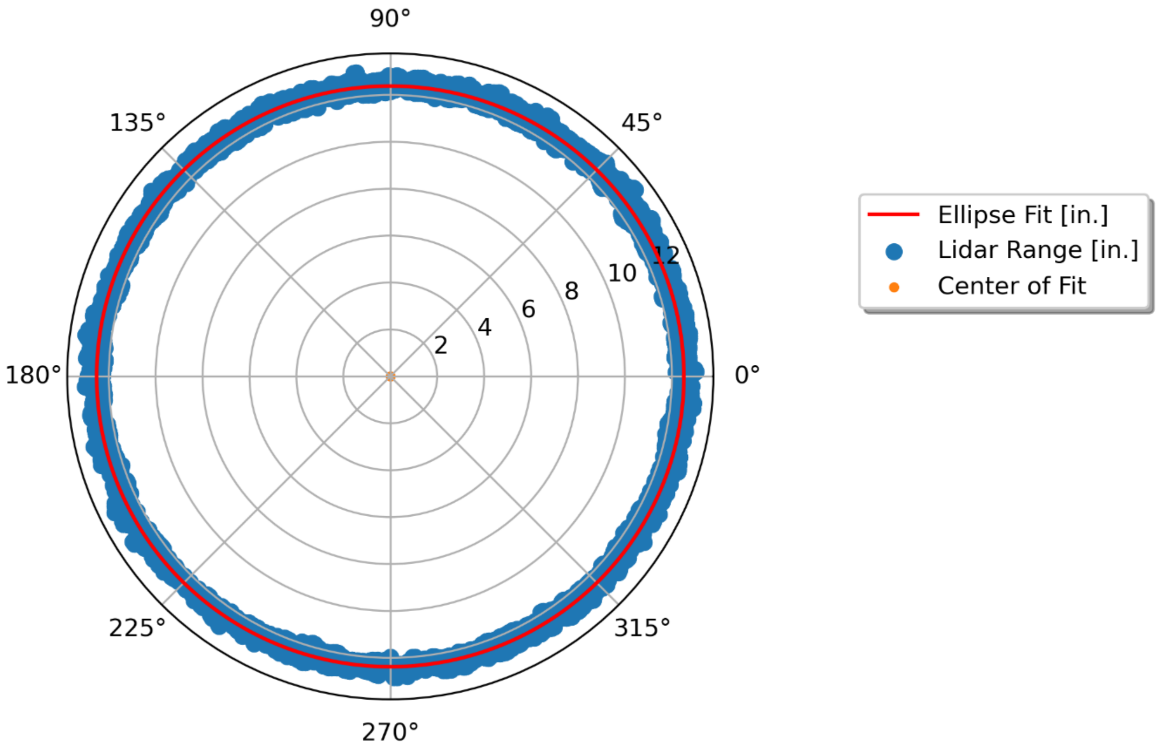

Figure 8 Calibration Data Run 1

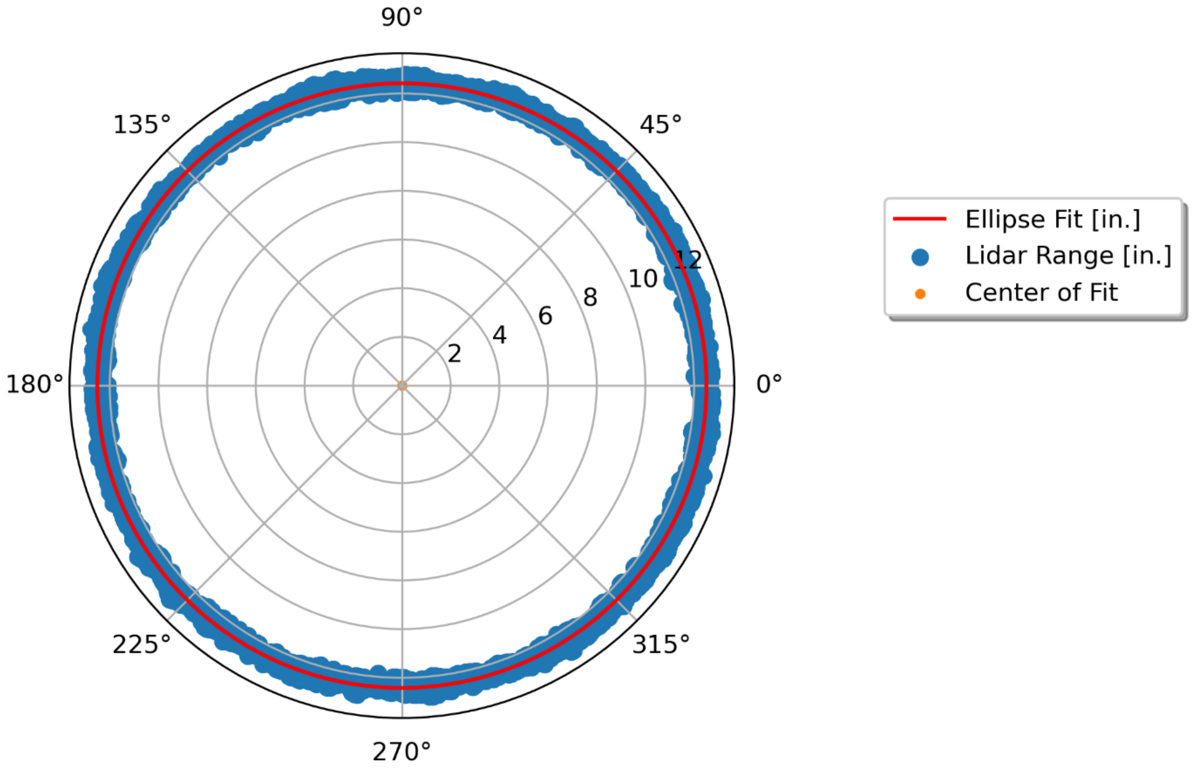

Figure 9 Calibration Data Run 2

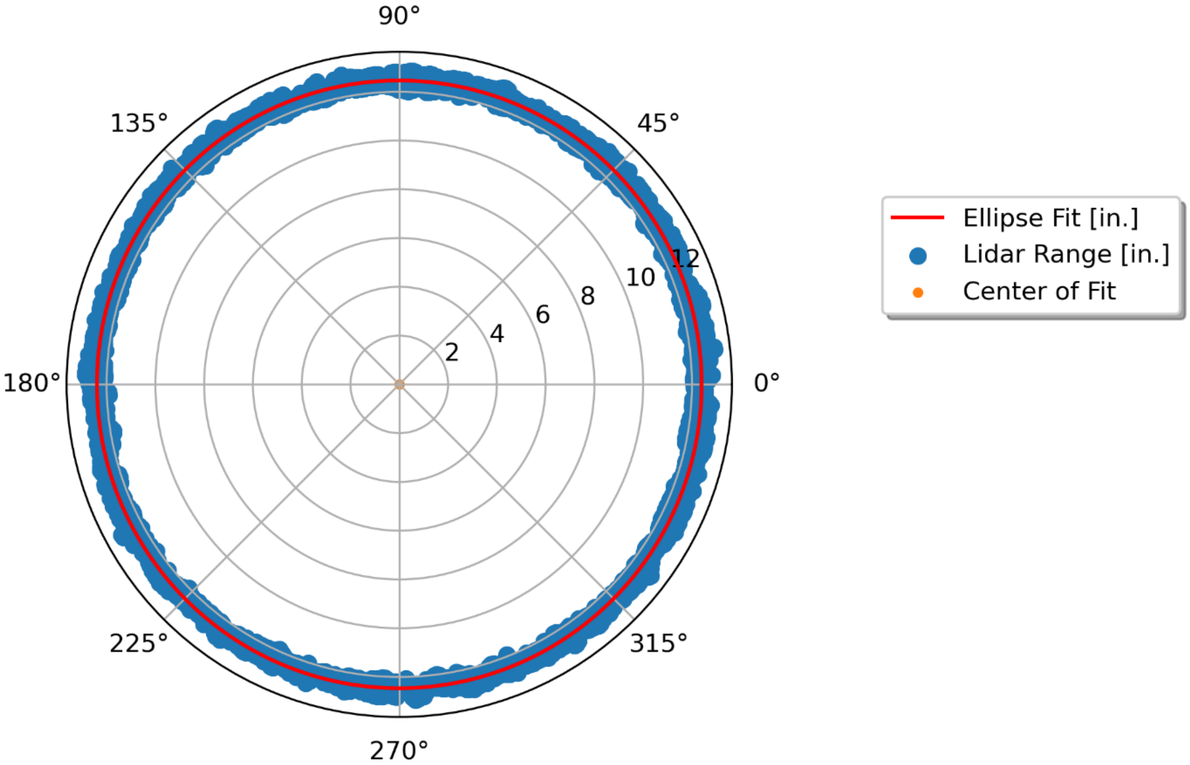

Figure 10 Calibration Data Run 3

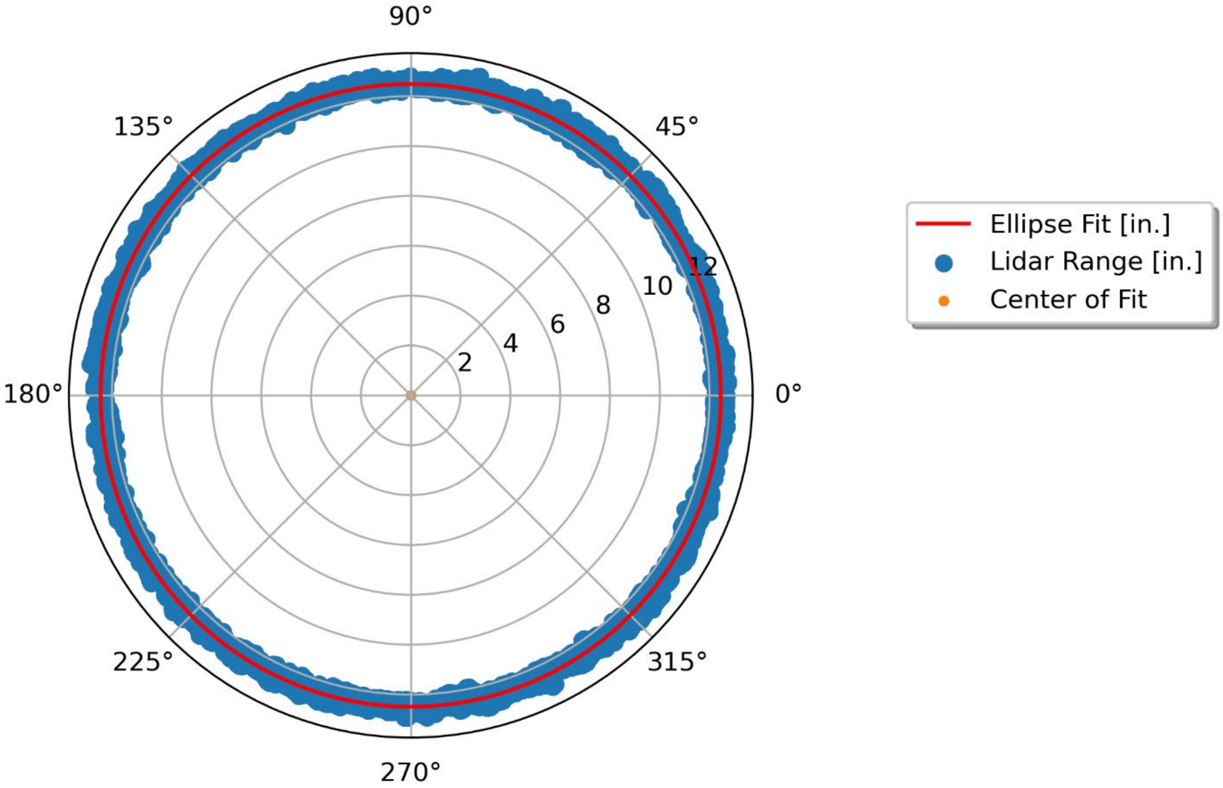

Figure 11 Calibration Data Run 4

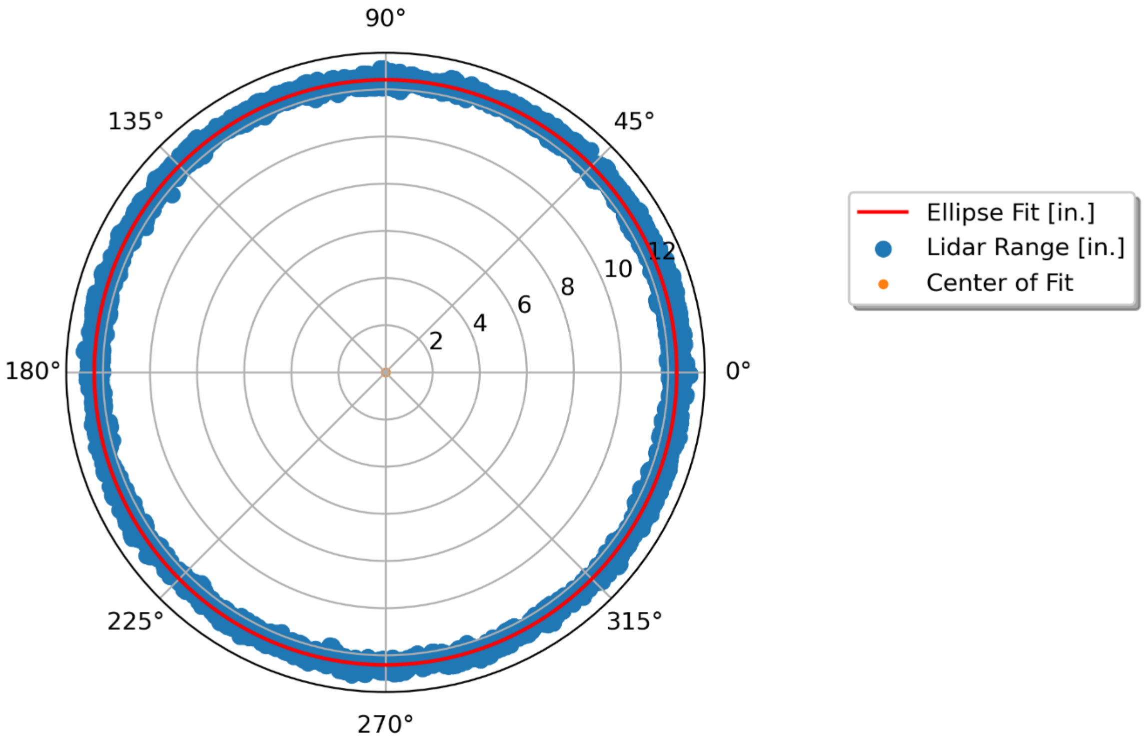

Figure 12 Calibration Data Run 5

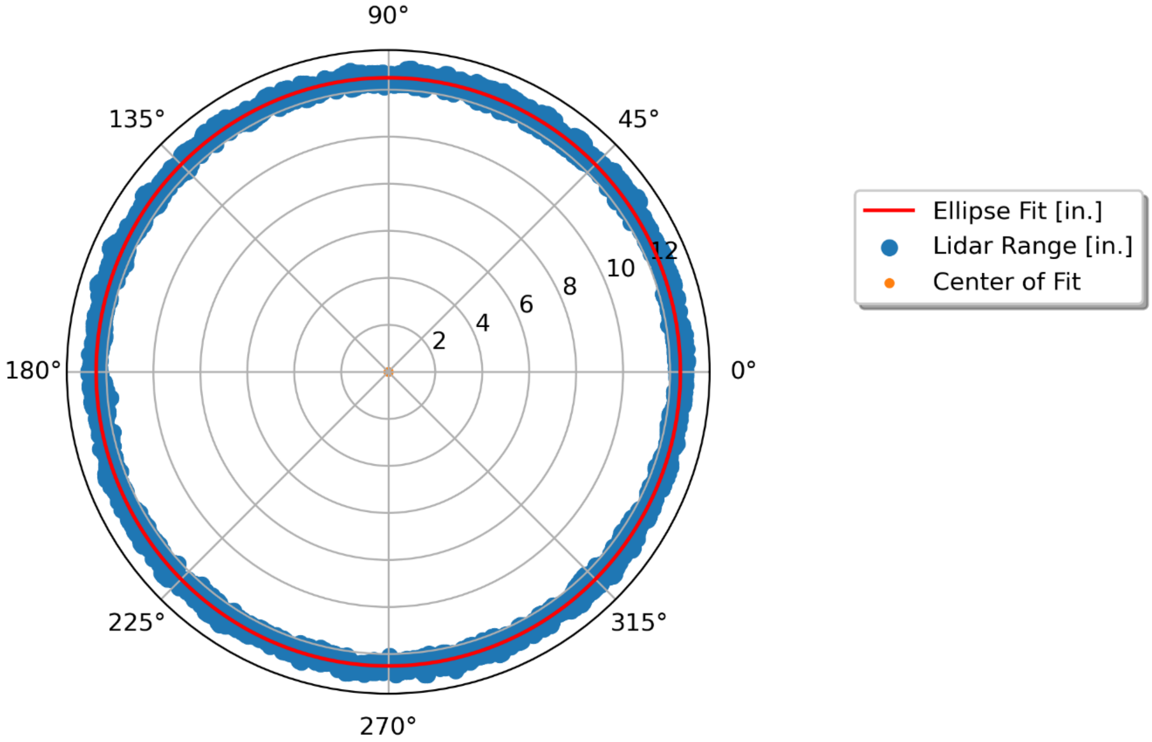

Figure 13 Calibration Data Run 6

Field Evaluation of the RSDMM Prototype

The Ohio University team was unable to complete field evaluation testing as originally proposed for this project. Delays in the initiation of this project in the Spring of 2020 due to the COVID-19 pandemic delayed delivery of the Turtle Rover until February 2021 at which time weather conditions did not permit for full-scale field evaluation of the unit by the research team. Preliminary data collection was conducted at the site of the research project titled "Field Verification of Structural Performance of Thermoplastic Pipe Under Deep Backfill Conditions" [Sargand et al., 2002] to ascertain the functionality of the Turtle Rover and the LiDAR system. Issues included the inability of the rover to operate under temperatures below 34°F (1.1°C). In addition to the minimum operating temperature, field operations showed that the internal temperature of the rover should not exceed 158ºF (70ºC), otherwise the system will shut down automatically. The field run served to verify the proper operation of the Turtle Rover and familiarize OHE staff with its operations.

Conclusions and Recommendations

In order to provide ODOT with an efficient and cost-conscious means of measuring the inside diameter of buried pipe, the Ohio University team built a robot based on the Turtle Rover provided by ODOT. The robot includes a forward-looking video camera, LiDAR system, LED lighting system, and odometer attached to the driving wheels. The rover will be controlled with a Microsoft X-Box controller and a pi-top base station. An operating manual is provided to aid in the operation of the rover.

Issues encountered included the inability of the rover to operate below 34 °F (1.1 °C) and internal temperature not to exceed 158 °F (70 °C), as well as a minimum pipe diameter of 24 in (610 mm).

The LiDAR system was calibrated at the OHIO University Laboratories on a 24 in (610 mm) HDPE pipe.

Recommendations for the Turtle Rover is to conduct more rigorous calibration runs to include multiple size pipes and various pipe materials as well as extensive field testing to ascertain the robustness of the system.

References

Kawasue, Kikuhito and Komatsu, Takayuki. (2013). Shape Measurement of a Sewer Pipe Using a Mobile Robot with Computer Vision. International Journal of Advanced Robotic Systems. 10. 1. 10.5772/55261.

K. Matsui, A. Yamashita and T. Kaneko. (2010). "3-D shape measurement of pipe by range finder constructed with omni-directional laser and omni-directional camera," 2010 IEEE International Conference on Robotics and Automation, Anchorage, AK, 2010, pp. 2537-2542, doi: 10.1109/ROBOT.2010.5509851.

Shad M. Sargand, Glenn A. Hazen, Teruhisa Masada, Donald Schehl, Alan Moran, and Bashar Altarawneh. (2002). Field Verification of Structural Performance of Thermoplastic Pipe Under Deep Backfill Conditions, Final report FHWA/OH-2002/023 to Ohio Department of Transportation, September 2002.

Shad Sargand, Issam Khoury, Wallace Richardson, and G. Contreras. (2016). “Field Inspection of Corrugated High-Density Polyethylene Pipeline Network Under Heap Piles at Copper Mine Site in Chile”. ASCE *Journal of Pipeline Systems – Engineering and Practice*; Vol. 7, Issue 2, May 2016.

Appendix A. List of Materials Used in Turtle Rover

Component	**Description/Model Number**	**Cost**
Turtle rover	Turtle Rover Development Kit	$2,400.00
Servo	Traxxas 2056 High-Torque Waterproof Servo	$35.00
Lidar	RPLIDAR S1 360° Laser Scanner (40 m)	$650.00
Wi-Fi adapter	Alfa AWUS036NHV 802.11n High Power 5000mW Wireless-N USB Wi-Fi adapter	$45.00
Wi-Fi antenna	Alfa APA-M25 Dual Band 2.4GHz/5GHz 10dBi high gain Directional Indoor Panel Antenna	$20.00
Microcontroller	Adafruit ItsyBitsy M4 Express	$15.00
9-DOF IMU	Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout	$35.00
Rotary encoders	Romi Encoder Pair Kit, 12 CPR, 3.5-18V	$9.00
Controller	PowerA Enhanced Wired Controller for Xbox One - Black	$25.00
Pi-top	pi-top - Raspberry Pi Laptop	$320.00
Flashlight	2000 Lumen LED Tactical Flashlight	$20.00
Pi 4 heatsink and fan	Geekworm Raspberry Pi 4 Embedded Heatsink with Fan (P165-A)	$11.00
5-volt BEC	iFlight Mirco BEC 5V 3A / 12V 2A	$4.00
Miscellaneous parts	Includes, screws, washers, bolts, RTV silicon, PLA Plastic, and other components	$1000.00
Total		$4,589.00

ORITE • 231 Stocker Center • Athens, Ohio 45701-2979 • 740-593-0430
Fax: 740-593-0625 • orite@ohio.edu • http://www.ohio.edu/orite/