Pipe Mapping in 3D Space Proposal

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***Abstract*—For hundreds of years pipe systems have been used around the world to transport important resources over large distances. Today, the need for finding these old buried pipe systems is ever-growing as infrastructure continues to expand. Industrial pipe detection and location in the past, such as total stations, RTK, and LiDAR, have been the standard for many years. Recently, advances have been made to more efficiently locate these larger infrastructure networks, but residential pipe mapping has remained primitive. This paper assesses the current methods for residential pipe mapping and proposes a new method that is both cheaper and more efficient.**

***Index Terms*—Capstone Design, Pipe Mapping, Residential Pipes, 3D Mapping**

I. Introduction

Since the beginning of the 1700's the United States has been laying an infrastructure of piping across the nation to supply essential resources, such as water and gas, to commercial, government, and residential buildings. In December of 2021 the government announced a $2.9 billion infrastructure bill that will replace all residential lead pipes with copper pipes. This imposes the question of how maintenance crews will find already existing pipe networks at a low cost without the danger of heavy digging equipment.

Currently, methods exist for the detection of large industrial pipes but there is a lack of such technology for small residential pipes. This document proposes a new way of mapping pipe networks using a small probe to record depth and location information while harmlessly traversing the pipe. The team's objective is to create a probe based system to traverse and map variable sized underground pipe networks in 3D space within an acceptable margin of error. While implementing the mechanical traversal of the pipe is not within the scope of this project, the primary goal consists of setting up the base technology for 3D mapping and real time information transmission inside a pipe.

The structure of this paper is as follows. The background of current detection and location methods, in both industrial and residential environments, will be discussed in more detail in Section 2. The constraints and specifications of the team's proposed method will be discussed in Section 3. Section 4 will expand on the current obstacles seen by the team with the given constraints and will discuss how the team will be measuring success with each experiment as well as the entire project. The relevant standards, broader impacts, and ethical considerations will be discussed in Section 5, and Section 6 will cover the timeline and required resources established by the team.

II. Background

To understand why a new method for pipe mapping is greatly needed it is first necessary to understand the current methodologies. While piping has been around since early recorded time the methods for finding buried pipe networks have largely been neglected. In recent years accomplishments in pipe detection and location have been made, however, they still lack the cost effective and ease of use that many technologies today offer. In this section an overview of current pipe location methods in both industrial and residential contexts is discussed. Further analysis on the safety and cost implications of both methods is explored in more detail.

A. Current Industrial Pipe Locating Methods

Industrial Pipe locating is an important technology for infrastructure expansion and repair leading it to be the more researched domain. Previous methods included total stations, real-time kinematic positioning (RTK), and light detection and ranging (LiDAR). New research in inertial mapping has led to advances that create a 3D model through the detection of pipes ranging in diameters from 29-34mm to 90-1500mm for distances of up to 2 km with a precision of up to 15 cm in XYZ space [1]. While these are helpful they suffer from the inability to find cross-bores (natural gas lines that intersect sewage lines) and cause unwanted pipe damage when excavating.

Currently, the best methods for detecting pipes are by using electromagnetic wants (EMI) or ground penetrating radar (GPR) pushcarts. These methods lead to a safer and cheaper way of locating pipes but must be conducted at the time of installation. However, it remains a challenge to locate pipes installed with horizontal drilling using this method.

B. Current Residential Pipe Locating Methods

Residential pipe location is still very primitive and commonly requires large and dangerous equipment. If the pipe network cannot be established from the entry and exit point of the pipe wanted a grid search must be conducted on the property which can be time consuming and expensive. To better understand the implications of pipe location it is necessary to understand the contexts in which they are used. Pipe replacement is the most common reason one may need to find an underground pipe network. There are two main types of pipe replacement; trenchless and traditional.

Trenchless pipe replacement has two main types: pipe lining and pipe bursting. Pipe lining essentially lines the old pipe with epoxy-impregnated liner thus creating a new pipe inside the old. Pipe bursting replaces an old pipe by taking a new high-density polyethylene (HDPE) pipe and pulling it through. The old pipe busts the old into pieces and replaces it in the same location. This is effective for longer pipes but has limitations for anything that is not a straight horizontal pipe.

Traditional pipe replacement is the most common method and requires the need to dig through various materials that may be covering the pipes.

Even though trenchless pipe replacement can be used to avoid digging and locating pipes the problems and cost are still large enough to consider another method.

C. Safety and Cost

Both residential and industrial pipe location can be extremely time consuming and expensive and can require dangerous machinery to access the network. For an individual the equipment and expertise may be hard to acquire. For a business it may be difficult to hire a contractor in time to use the equipment needed and may extend or jeopardize the success of the job in a timely manner.

Trenchless pipe replacement cost depends on the methods used. If pipe lining is used a rough cost of \$80 - \$250 per foot is standard with an average of \$160. For a complete pipe replacement in a standard home the range is \$6,000 - \$12,000. If pipe bursting is used a rough cost of \$60 - \$200 per foot is standard. A complete pipe replacement can cost upwards of \$3,500 - \$20,000. [2]

Traditional pipe replacement cost can vary depending on the success of pipe location. The following data assumes that the pipe was found on the first attempt of excavation. The average cost to dig and replace a pipe is \$50 - \$250 per foot. A small pipe replacement can be \$3,000 - \$6,000 and can increase to \$5,000 - \$13,000 for repairs longer than 50 feet. The cost of replacing sod, landscaping, concrete and labor contribute to the cost as well.

When looking at the CAT rental store [3] the necessary tools for underground pipe installation include an excavator, trencher, trench shoring equipment, pipelaying underground laser, pipelayer, and compactor. The cost of this equipment is estimated to be \$1,574 per day and could be more expensive depending on the job. One of the most important costs to evaluate is the injury or death of one or more persons during these practices.

One of the most important costs to evaluate is the injury or death of one or more persons during these practices. With the extended use of heavy machinery and hydraulic equipment there is a possibility of injury or death. Using the method in this proposal, the team aims to lower the cost and liabilities of pipe related jobs by more effectively and safely locating pipe networks.

III. Constraints and Specifications

With a background on pipe replacement methods and the cost of trench digging one can now understand the basic constraints and specifications that may be considered by the design team. The specifications are constraints held by the team, and stakeholders, that will help define success or failure. The constraints are defined by standards and physical limitations on the design. This section will discuss the specifications needed by the team and possible users of the technology and constraints defined by standards and physical limitations.

A. Specifications

The current methods of pipe location can be costly and dangerous. As such, the largest specification for the project is to lower cost and decrease heavy machinery use by accurately providing pipe network mapping. Retrievability and reusability will be paramount in ensuring the cost and benefits remain at a level where the technology will be worth using.

Retreivability will be maintained by the use of a string that will be used to guide and move the probe through the network. Reusability will be maintained by the ability to reset the probe memory state every time it needs to be reused.

Specifications will be designed to take potential users and government and organization standards in to account.

B. Constraints

The environment in which the probe will be operating is a 1” to 4” in diameter pipe network that has 90° turns and complex piping structures. This defines a constraint for small and flexible electronics and the need for a transmission domain that can penetrate the PVC and possible materials surrounding the network.

The probe size should not pose a problem due to the availability of extremely small sensors and PCBs. The method that the team plans to use to avoid problems with 90° turns is splitting the probe into modules so the bending and turning of circuit boards and sensors will not be an issue.

The constraints for this project have been well thought out and will not pose a problem in the team’s final design.

IV. Success Measurements

Success must be measured to account for abnormalities in testing and inevitable error, however, it must also meet strict standards that adhere to statistically informed specifications.

The team's success is split up into multiple sections to better and more accurately determine if the system operates correctly and meets specifications. The experiment designed by the team takes into account each of the sections listed below. The device will be run through 10 different PVC pipe networks using a rope attached to the device pulling it through. 10 trials will be run on each of the networks that are built to test for accuracy, speed, and battery life. Using the data that will be collected from these trials, an accurate measurement of the success rate and therefore overall success of the build can be generated.

A. Mapping Accuracy

The device will need to map the pipe that it is traversing within a reasonable margin of error. The test will be considered a success if it can accurately map a pipe network within a 1" radius of the actual network.

B. Mapping Speed

The device will need to be tested for the appropriate speed at which it can accurately retrieve data and still be efficient. Successful efficient speed will be acquired if the probe can move at least 6 in/sec and still obtain accurate data.

C. Battery Life

Battery life of the device is especially important as it would be inefficient be unable to map an entire pipe in one charge. Battery life will be considered a success once the device can map at least 1000 feet of pipe on one charge / battery replacement.

D. Cost

The cost of the device must be justified by keeping the value added higher than the cost of the device. This will be calculated as the team designs and tests the build. If each of the previous categories are satisfied within a reasonable cost the cost will be considered a success.

V. Standards, Impacts, and Ethics

There are many standards that this project will need to adhere to, most of which have been set forth by either professional standards organizations or federal agencies. These standards will act as constraints that will enable the design of a safe and effective final product.

Alongside the relevant standards, there are numerous externalities that must be considered throughout the design process and implementation of the proposed pipe mapping system. While some of the possible externalities are quickly identifiable from the beginning, some may only become apparent throughout the course of the project, and will likely vary as the specific design changes.

A list of standards relevant to this project are listed in the corresponding subsection below, followed by a more focused look at some of the possible externalities.

A. Relevant Standards

- National Electric Code (NEC)
  - Article 460: Capacitors
  - Article 470: Resistors and Reactors
  - Article 480: Storage Batteries
- Environmental Protection Agency (EPA)
  - Mercury-Containing and Rechargeable Battery Management Act
- Federal Communications Commission (FCC)
  - 47 CFR 15: Radio Frequency Devices
- Institute of Electrical and Electronics Engineers (IEEE)
  - 1293: IEEE Standard Specification Format Guide and Test Procedure for Linear, Single-Axis, Nongyroscopic Accelerometers
- IPC
  - IPC-A-600: Acceptability of Printed Boards
  - IPC-A-610: Acceptability of Electronic Assemblies

B. Externalities and Ethical Considerations

When considering the possible externalities that could stem from this project, one of the foremost concerns is the potential for the device to become lost, stuck, or otherwise irretrievable from the pipe system that it is mapping. An event like this not only poses a potential risk to the pipe network, and thus a risk to the property of the client, but also raises questions regarding the optimal method for data preservation in the event that the probe is recovered after such an incident.

The probe must also be constructed in such a manner that it will neither damage nor introduce potentially unwanted contaminants into the pipe network, whether during normal operation or in a failure case as described in the previous paragraph. This means that special care will need to be taken in regards to choosing the material making up the outermost surfaces, as well as properly protecting any potentially harmful chemicals contained within the device, such as battery acid. While PVC material is relatively resistant to such acid [4], lead pipes are a different story.

VI. Timeline and Resources

The timeline of the project is a very rough estimate of times and objectives for each member, and the team as a whole, to meet. The resources are the collective abilities of each of the team members that will enable the team to complete the proposed project. In this section, a detailed specification for a brief timeline and resources necessary for the project will be discussed in depth.

A. Timeline

Currently the tasks are divided into their subsystems for the project and distributed to the most experienced team members in that area respectively. Benjamin Ask is working on the research and design of the storage subsystem. Caleb Thorne is working on the research and design of the transmission subsystem. Adison Heathcott is working on the research and

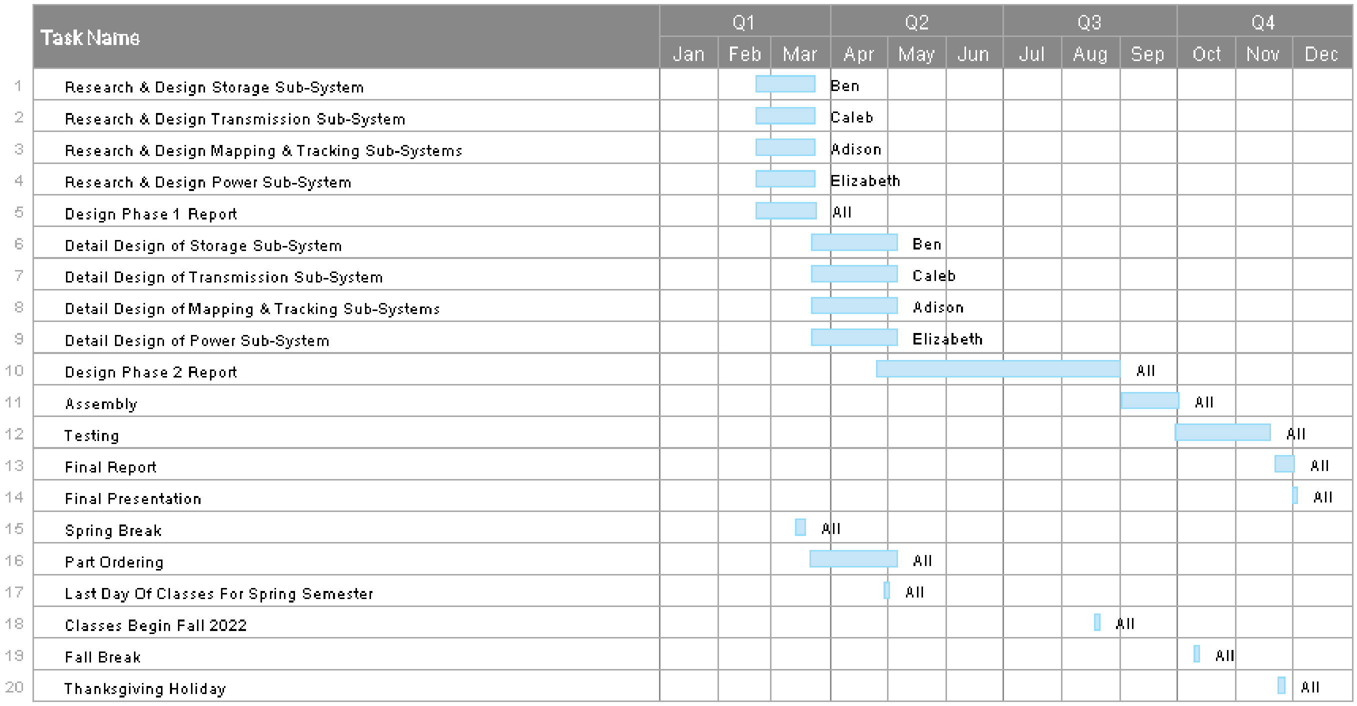

Fig. 1. Timeline Gannt Chart.

design of the mapping and tracking subsystems. Elizabeth Russell is working on the research and design of the power subsystem. “Fig. 1” shows the timeline in which the team expects to finish each of the subsystem checkpoints.

B. Personnel

This section summarizes the skills that each member of the team possess that will most likely be utilized during the designing, building, and testing of the mapping probe. These skills were also taken into heavy consideration when deciding what subsystems each member would handle.

Caleb Thorne

- PCB Design
- Telecommunication
- 3D Modeling
- Prior knowledge of power systems
- Matlab

Benjamin Ask

- Prior knowledge of piping work
- Matlab
- Digital Logic Design
- Embedded Systems
- C++ / C

Adison Heathcott

- PCB Design
- Embedded Systems
- Digital Logic Design
- Matlab
- C++ / C

Elizabeth Russell

- Matlab
- Labview
- Electromagnetics
- Telecommunication

C. Resources

The necessary equipment, average cost per item, software, and total estimated cost of the mapping probe are compiled in “Table. I”. The expected cost was determined by calculating the average of the most cost efficient and advanced models of the parts. This equipment is essential as the theoretical design of the probe consists of four modules: transmission, mapping / tracking, power, and memory storage. To implement the transmission module a transceiver will need to be utilized, tracking and mapping will use a gyroscope and Matlab, power will use batteries, and the storage module will vary in type and amount of memory depending on the project needs.

D. Required Equipment and Software

- Battery
- Transceiver
- PVC
- Memory storage
- Gyroscope
- Matlab
- Labview
- C++

TABLE I
EXPECTED COST

Equipment	*Amount*	*Average Cost*	*Maximum Cost*
Battery Pack	1:4	23.7	94.8
Transceiver	1:3	41.05	123.15
PVC	20':40'	44	88
Memory storage	1:2	387	774
Gyroscope	1:2	11	22
Matlab	1	0	0
Labview	1	0	0
C++	1	0	0
Total Cost		506.75	1101.95

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