Design Phase 1

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I. Introduction

1) Problem Statement: The main issue in pipe infrastructure is the money and time lost to locating the 'lost' pipes where the original surveys either were not recorded or were destroyed [8] [9]. The 'lost' pipes may malfunction due to a leak, need to be connected to a new system or may be ruptured due to construction that had no pipe on record which could be disastrous if the pipe were to be filled with gas or water. Issues that may result in a ruptured pipe can be as small as a leak to accidentally creating a spark and igniting gas in a pipe [7].

2) Document Summary: This project's goal is to create a probe that can be guided through a length of pipe (20 to 40 feet of pipe) and collect data. This data will then be uploaded through a wire to a computer, which will receive, visualize, and plot the collected data to create a map of the pipe system. The subsystems of the resulting design are Power, Storage, Data Analysis, and Data Collection. These systems are atomized in Figure 1, but a short description of said subsystems is as follows: Power – contains the system concerning the supply of power to the system Storage – contains the system concerning the storage of data gathered by the probe Data Analysis – contains the system concerning the calculation on an external device of the data collected Data Collection – contains the system concerning the collection of data from the probe Movement - contains the system concerning the traversal of the probe through the pipe.

3) Expectations: A few specifications and standards for the pipe network that the team will test in are 1"-4" diameter pipes, 90 degree turns only, such as 'elbow joints' no 'T-joints', and empty pipes with no water or gas contained within. Other concerns that may happen are things such as possible damage or error with the collecting of data which the team is planning to solve by having a redundant system to average with the main collection system to solve any error with the data collection. The ideal functioning of this probe and accompanying code will result in a probe that can map pipes in residential areas and will greatly reduce the cost of locating and uncovering said pipes.

II. System Overview

A. Data Collection Subsystem

1) Microcontroller: The microcontroller is the center of the probe and will be doing the most in terms of computation and power usage for the system. The team believes a low power STM microcontroller and custom board will be the most cost and performance efficient option. The team also has more experience in programming STM microcontrollers specifically, so the development of software should be easier.

Due to the constraints from the peripheral hardware and software the team needs to lay specifications on the microcontroller subsystem. This will assist in finding an adequate microcontroller that will support the needed hardware.

Firstly, the microcontroller must be a 32 bit device to adequately support the 12 to 16 bit data it will be receiving from the peripheral IMU's. It will also need to support memory addressing for the storage subsystem, which may be larger than 16 bits can support easily. Next, the microcontroller must have an adequate number of GPIO pins to support the peripherals and storage hardware. As of now the estimated number of minimum GPIO pins necessary are 50. This will allow extra pins to exist in case of need later and will be supported by a wide variety of microcontrollers. Finally, the microcontroller must allow an external clock source to be input for more accurate clock signals, and must support I2C, SPI, or USART for peripheral communications.

Each of the systems in the data collection subsystem will connect to the microcontroller using the pins of the microcontroller. Most systems will connect through either power or GPIO, however, some systems will connect to special pins on the chip, such as reset. The connections and their relationships will be discussed under each subsystem.

2) Clock: The clock subsystem is important since most microcontrollers do not have stable internal clocks. Most

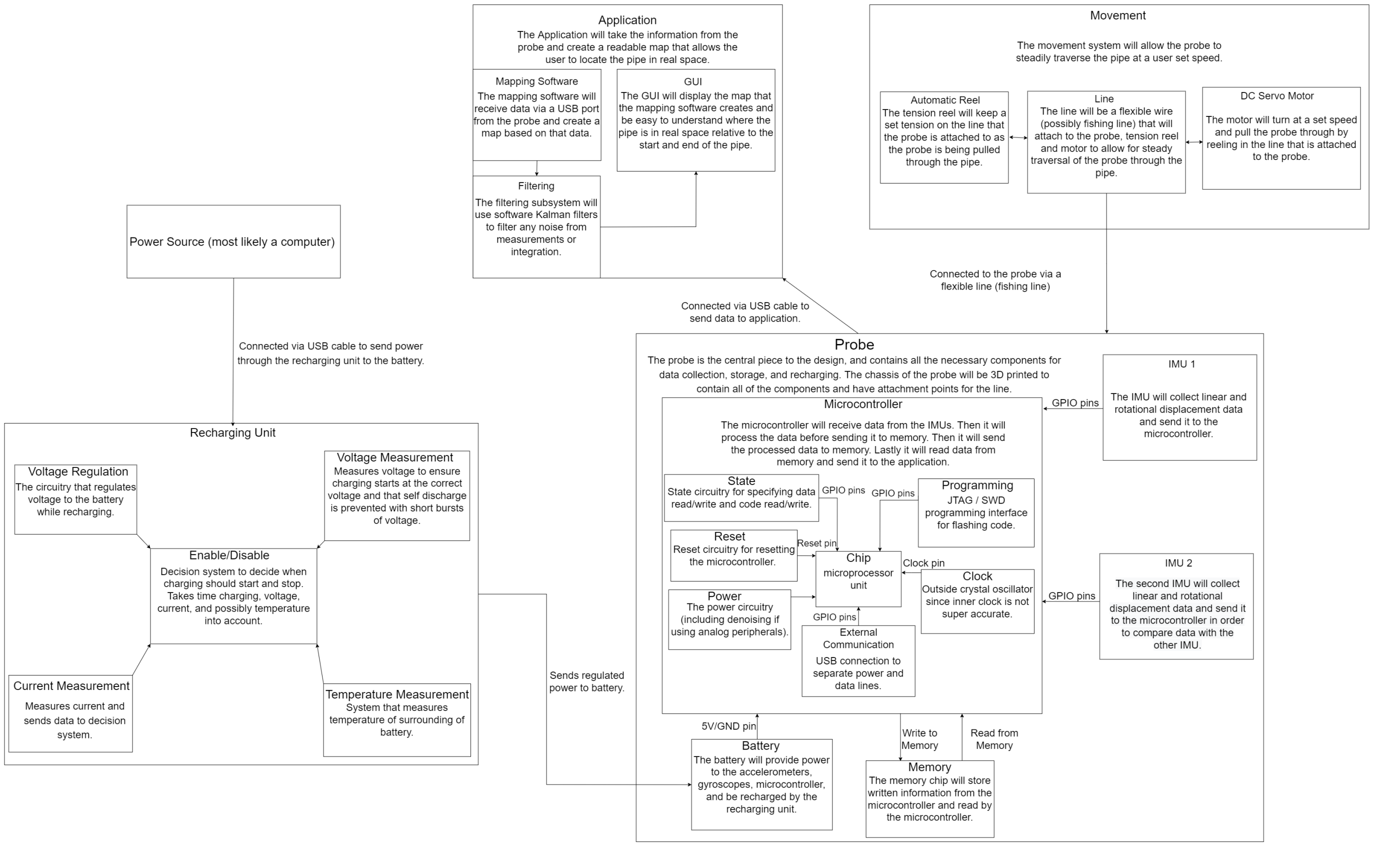

Fig. 1. Block Diagram.

internal clocks are made of resistors and capacitors which can cause the clock signals to be inaccurate and noisy. [5]

Timing is very important for calculating positions, communicating with peripherals, and ensuring the correct amount of power is used. Peripherals such as I2C and SWD need accurate clock signals to function correctly. The clock is also one of the most power consuming parts of a microcontroller and needs to be exact to ensure battery life calculations are accurate.

The teams solution is to connect an external crystal oscillator to the microcontrollers pins to supply a more precise clock signal to the device.

3) Programming: The programming subsystem will allow the team to upload new software to the device much easier during development and testing. Most microcontrollers do not support software uploading systems out of the box, so a system needs to be developed to allow the user to upload new software from a USB connection.

JTAG and SWD are the main standards for communication when it comes to software uploading. SWD uses two GPIO pins, only supports ARM architecture, and supports printing debug information. JTAG uses four GPIO pins and supports multiple architectures including ARM. [6]

The team has decided JTAG will be the most beneficial due to its wide support for architectures. The system will need to have connections to the microcontroller GPIO pins and the USB port.

4) External Communication: The external communication subsystem will take care of power and data from the USB attached to the probe. The circuitry will determine what pins from the USB are sent to the power subsystem, and what data pins are sent to the correct subsystem for retrieval or reprogramming. The physical representation of this on the board will be a USB socket and simple wiring for splitting the input pins.

5) Reset: The device will always be under the threat of software or hardware bugs that could lock up the system. To counter this a reset system will be implemented onto the device. This will give the user a button or switch to interact that will be connected to the reset port on the microcontroller.

Hard reset will always be accomplished by turning the probe off and resetting the power. This subsystem will supply the user a fast and efficient way to reset the software and peripherals without interrupting power supply.

6) State: The system will have multiple different states it can be in for operation. These states need to be defined in ways where the user can see the current state, and set new states.

For this a switch will be used to set the microcontroller and peripheral hardware into whatever state it needs. This will include a state for collecting data, retrieving data, writing new code, and enabling / disabling the device. This system will be connected to the microcontroller through GPIO pins that will tell the software what state to run in.

7) Acceleration Measurements: Measuring the acceleration of the device as it traverses the pipe is an integral part of the mapping process. Rather than using discrete accelerometers and gyroscopes, this project will utilize inertial measurement units (IMUs) in order to collect the position data. One component of an IMU is its 3-axis accelerometer, which will be used to measure the device's acceleration through the pipe.

The accelerometer has very few constraints since it creates more than it needs to adhere to. Firstly, most accelerometers have more than adequate sensitivity for the project. Secondly, most accelerometers support I2C, SPI, USART, and temporary data storage which will be supported by almost any microcontroller. Most accelerometers also run at a high enough frequency to have more than enough data points and to minimize the error gathered through the process.

8) Rotation Measurements: Keeping track of the device's rotation is crucial for the task of mapping, as the rotational data will quantify any directional changes that the device makes. This measurement of the device's rotation, which will be taken by the IMUs 3-axis gyroscope, will be used alongside the acceleration data in order to obtain an accurate representation of the area traveled by the device.

While the gyroscope is a separate component it adheres to the same constraints and specifications as the accelerometer since they will be coupled into the same device.

9) Error Measurements: There are a number of errors that can occur when using IMUs [1], though there are existing methods to help mitigate these errors. While most error reduction in this context will be accomplished by proper filtering, using multiple IMUs in tandem has been proven effective [2] in reducing the amount of IMU bias errors with respect to time. With this in mind, the team does intend to implement two IMUs in the design as a form of error prevention.

In regards to combating erroneous measurements via proper filtering, there are a few options that may be useful for this project. Utilizing a Kalman filter will likely be the best option however, as this method is specifically useful for predicting a device's location over time. [3]. Kalman filtering is also well documented as a filtering method for IMUs in particular [4], which makes it a promising method of error correction for this device. This filtering will be done via computer software once the device is connected.

B. Storage Subsystem

1) Memory Chip: The memory chip subsystem will handle the storage and retrieval of the data sensed by the probe. It will need to be able to hold at least 5000 feet of data and keep the data over a reset or power off signal. The memory chip will be connected to the microcontroller through GPIO pins and will be connected to the power subsystem through the power and ground lines.

The memory needs are difficult to predict, however, they can be roughly estimated. The worst case accelerometer data collection will be 1000 Hz with 16 bits of data. The longest pipe the team expects to support is 5000 feet. An estimated 20 minutes will be needed to traverse the pipe. At 20 minutes the device will collect around 10 MB of data. This will be the teams estimated constraints on the memory size for the storage subsystem.

C. Power Subsystem

1) Battery: As this device will be designed to operate without a constant supply of wired power, a rechargeable battery (or series of batteries) will be necessary in order to keep it powered as it traverses the pipe. The battery subsystem will have connections with the voltage regulation, voltage measurement, current measurement, heat measurement, and microcontroller subsystems.

To properly support the hardware the team is planning on getting a battery that at least supports a maximum 3.6 V - 5 V voltage with 1Ah. With the lower amperage needs of all the devices 1Ah should suffice and will be decently easy to acquire.

2) Voltage Regulation: The voltage regulation subsystem is responsible for regulating the battery voltage during the recharging process, ensuring that neither the battery nor device are damaged by exposure to excessive voltage. This subsystem will be connected to the battery subsystem, the voltage regulation subsystem, the current measurement subsystem, and the connected charging source.

3) Voltage Measurement: The voltage measurement subsystem will actively measure battery voltage in order to ensure that the charging process starts at the correct voltage. This subsystem will also help to correct self discharge via short bursts of voltage when necessary, and will be connected to the enable/disable switch, the battery subsystem, the voltage regulation subsystem, and the current measurement subsystem.

4) Current Measurement: The current measurement subsystem will be responsible for ensuring the correct amount of current is delivered to the battery during the charging process, as well as determining when the battery is full or not. This system will be connected to the battery, the voltage regulation subsystem, the voltage measurement subsystem, the enable/disable switch, and possibly the heat measurement subsystem.

5) Heat Measurement: The heat measurement subsystem will ensure that the battery does not get too hot during recharging and cause damage. This system will also be able to detect over current in extreme cases, since that will be the cause of excessive heat dissipation. This system can either be designed as a small temperature gauge or can be integrated into the current measurement subsystem. It will be connected to the enable / disable subsystem so it can disable all power transfer when heat is getting too high.

6) Enable / Disable: The device will need to be enabled and disabled both manually and automatically. The user will be able to turn on and off the device using the manual power switch. The device will also be able to automatically enable and disable power during recharging to protect the battery.

This system will be connected to the current measurement subsystem, voltage measurement subsystem, heat measure-

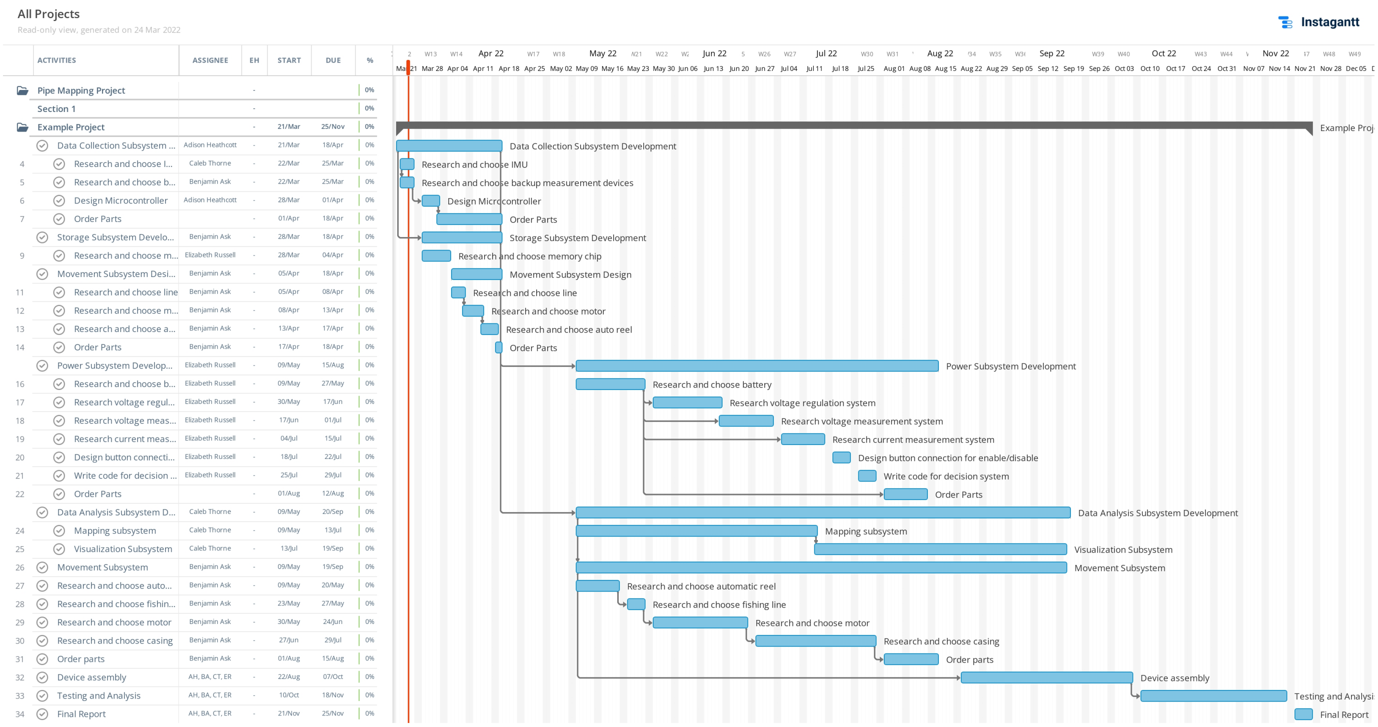

Fig. 2. Gantt Chart

ment subsystem, and the microcontroller subsystem to power off the device when needed. The voltage measurement will watch for when the battery falls below a certain voltage. The current measurement will ensure the correct amount of current is supplied during recharging and will determine when the battery has received the correct amount of amperage. The heat measurement subsystem continuously check the temperature of the battery to ensure the battery is not damaged. Finally, this subsystem will also be connected to the microcontroller to turn the system on and off when the user needs.

D. Data Analysis Subsystem

To minimize the work and complexity of the microprocessor, the job of calculating mapping and visual data has been moved to an external program. The program will acquire data from the device using a USB and will use various programs to convert the acceleration and rotation data into 3D position data. It will also calculate and minimize error with software filters.

1) Mapping: The mapping application will be implemented on MATLAB due to its helpful libraries and strong computational power. The program will first acquire the acceleration and rotation data, convert them into 3D positional data, and filter out any noise or drift caused by integration. Then the points can be converted and charted to show distance, lengths, and other important information for location.

2) Filtering: A large part of the application will be filtering out extra noise produced by the variability of the gyroscopes and accelerometers. For this, the team will use software Kalman filters in either Matlab or Simulink.

3) Visualizing: The visualization application will be implemented on both MATLAB and any 3D model program possible, such as 3D viewer on Microsoft Windows. The program will first take the 3D data and convert this data into vertices that can be rendered to visibly show the pipe layout. These vertices will give users the ability to view to 3D pipe network using any program that will render obj files.

III. Constraints, Specifications, and Analytical Verification

A. Power

The power subsystem must be capable of supplying 3.6V to 5V to the device, as this should be sufficient for powering the microcontroller as well as its attached peripherals. In addition, the battery must be able to store at least 1 Ah of charge, which should be sufficient for the low-power needs of an STM microcontroller and the sensors. Many STM microcontrollers and IMUs come equipped with various options for power-saving modes, which will also help to conserve battery usage on these already low-power devices. This battery must also be rechargeable, which will place a constraint on what type of batteries can be used for this project. Finally, as the device will begin recharging when plugged into a computer, the power subsystem will need to be capable of receiving input power via USB ports of a computer. Depending on what version the USB ports are (2.0 or 3.0), the input voltage to the power subsystem will differ, which means that the power subsystem will need to be capable of accepting a range of possible input voltages.

In order to verify that the specifications of the power subsystem are met, analysis may be performed via simulation software, such as LTSpice or Multisim, as well as via manual calculation using principles of circuit design.

B. Storage

The storage subsystem shares a mutual constraint with the microcontroller, as the memory chip will need to exchange information with the microcontroller at the appropriate times in the clock cycle. In order to meet the specifications defined in Section II.B of this document, the memory chip will be capable of storing 100 MB at minimum. In order for the memory chip to retain the data when the device is powered off or reset, as also specified in Section II.B, this subsystem will need to be designed with a nonvolatile variety of memory. The team believes that using a flash memory chip will be a suitable option to meet this design specification. This subsystem, like most of the other subsystems, will also be constrained by the physical size restriction placed on the device as a whole (being small enough to traverse a 1" to 4" diameter pipe). The memory chip chosen must be as small as possible, while still meeting all of the above specifications.

The memory subsystem may be analytically tested via hand calculations. The team will verify that the memory chip will be suitable with calculations based on the microprocessor clock speed, read and write times of the chip in question, power requirements of the chip, and any other relevant information that needs to be considered.

C. Microcontroller

The microcontroller will need to be a 32 bit system, since the IMU output data is typically either 12 or 16 bits. In order to have enough pins for interfacing with all of the peripherals, the microcontroller must also possess a minimum of 14 GPIO pins, as well as the ability to support JTAG and I2C communication protocols. The microcontroller must also be capable of connection to an external clock generator, as the microcontroller design will implement an external crystal oscillator to aid in maintaining clock precision. The microprocessor in particular will also have constraints placed on it by the IMUs and memory chip, as the clock frequency of the processor must be high enough to support all of these peripherals while maintaining a suitable sampling rate for these devices. The microcontroller must also fit within the maximum footprint of the device, which will need to be small enough to traverse a pipe as small as 1" in diameter.

The microcontroller design will be analytically tested via a suitable emulator with STM32 support, such as Qemu.

D. IMUs

In order to ensure the highest data resolution possible from both of the IMUs, the team will select a device that provides 16 bit output resolution from both the accelerometer and gyroscope components. The IMUs must also draw a low amount of power, on the scale of milliamps, in order to ensure that the power subsystem is capable of supplying enough power to all device subsystems. The IMUs will also be constrained by the size specifications mentioned in the previous sections.

The IMUs will be analytically tested via Matlab and/or Simulink, as there are a variety of existing methods for IMU simulation on those platforms.

IV. Ethical, Professional, and Standards Considerations

A. Ethical Considerations

There are some considerations to be made regarding ethical design choices in this project, and the team has attempted to address all of them throughout the design process thus far. The primary ethical considerations for this project include the following.

1) Device Construction: The outermost surface of the device must 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. 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.

2) Device Lost/Stuck in Pipe: The possibility that the device could become, lost, stuck, or otherwise irretrievable from the pipe network is also an ethical consideration, as this event could potentially result in negative consequences affecting humans, structures, and/or the environment in certain failure cases. If the device gets stuck in an empty water pipe, and water begins to flow into the pipe before the device is removed, the blockage caused by the device could lead to pressure buildup that is excessive enough to cause the pipe to rupture. In this case, there could be direct harm caused to any individuals within close proximity to the ruptured pipe, as well as the surrounding structure. This break in the line would also prevent water from flowing to its intended destination, which could result in an outcome ranging anywhere from inconvenient to catastrophic, depending on what the water source was supplying. Depending on the chemical contents of the leaking water, (i.e., wastewater or drinking water), the burst pipe could also present an environmental hazard. In the case that the pipe carried gas rather than water, the pressure buildup resulting from a blockage caused by the device could result in a rupture of the pipe, which could then result in ignition of gas present in the line, depending on the properties of the gas.

With this being said, it is critical that the device be designed and constructed in such a manner that the probability of the device becoming stuck inside the pipe is minimized. The device will be designed with a minimal footprint, also taking into account the reduction in space that will occur in the bends of the pipe, such as 90 degree elbows.

B. Professional and Standards Considerations

The design of this project will adhere to all applicable standards, in both the professional and legal domains. The general PCB design, as well as the selection of its mounted components and peripherals, will adhere to the relevant IPC standards, which are listed below.

- IPC-2221B: Generic Standard on Printed Board Design
- IPC-A-600: Acceptability of Printed Boards
- IPC-A-610: Acceptability of Electronic Assemblies

The IPC standards will constrain this project in multiple ways, as these standards provide guidelines for virtually all aspects of PCB design [10]. Considering that the IPC standards will constrain the general layout of the PCB, such as trace widths, component distancing, and surface geometry, there will be a resulting constraint placed on which components must be selected in order to meet these overall standards. There will also be direct constraints placed on the components, as each component must be selected so that its rated values, such as power ratings, are not exceeded during any stage of the device's operation. The Environmental Protection Agency (EPA) imposes constraints on certain types of batteries via the Mercury-Containing and Rechargeable Battery Management Act. Given that many common coin-cell batteries contain mercury [11], and thus fall within the scope of this law, it is a possible constraint for this project. In the event that this project implements a coin-cell battery anywhere on the PCB, the PCB layout may need to be designed in such a way that the coin-cell battery is easily removable from the device in order to keep it in accordance with the law.

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