# Detect'O

Team 21 (PROJECT REPORT)

Atharva Sawant, Hriday Rathi, Khushi Goel, Priyanshu Singhal, Rahath Malladi

IL213: Innovation Lab & Grand Challenge Studio 3

# SECTION 1: PROBLEM IDENTIFICATION

## ROLES & RESPONSIBILITIES

| Team Role/Responsible | Member 1 | Member 2 | Member 3 |
|---|---|---|---|
| **Tech** | Rahath | Hriday | Priyanshu |
| **Design** | Atharva | Rahath | Khushi |
| **Logistics** | Atharva | Priyanshu | Rahath |
| **Communications** | Priyanshu | Khushi | Hriday |
| **Operations** | Rahath | Atharva | Hriday |

## BROAD PROBLEM STATEMENT

### PROBLEM STATEMENT

“Leaks in underground water pipes go unnoticed especially the smaller ones until they become bigger or very evident and finding the exact location of the leak is a long and resource consuming process.”

### GAP WE’RE TRYING TO ADDRESS

In contrast to the existing state of the field, several potential gaps could be filled in the development of future pipe inspection technologies and methodologies. Several instances include

1. **Developing advanced sensors and other technologies:** Currently, they do not always provide highly accurate data about the condition of pipes but could help to improve the accuracy and reliability of the data collected by these robots.
2. **Speed and Efficiency:** There is a need for approaches that allow pipe inspection to be performed more quickly and efficiently.

## HOW BIG IS THE PROBLEM?

Over some time, pipes can become damaged or degraded due to a variety of factors, such as corrosion or physical impacts. These issues can cause problems with the flow of materials through the pipes and pose a risk of leaks or ruptures.

The problem is two parts: the first is about the damage late detection causes. The second is about the whole process of pipe inspection itself. Leakage in underground pipes goes unnoticed until the damage is big or when it starts to cause inconvenience to people on a large scale. This is partly due to the inaction of authorities and partly due to the nature of the problem itself. This late detection is especially a major issue in low-pressure pipes where the pressure drop is not very evident until the leak is very big. The damage this causes is as follows:

A) Pipes with leaks can lead to the loss of materials being transported through the pipes.

B) Water from these pipes leaks out into the ground causing damage to infrastructure above the ground and underground too.

C) Water leaks out from these pipes and often causes roads to develop cracks, these cracks develop into potholes which are a major reason for road accidents, especially two-wheelers.

D) Water that leaks from these pipes causes health hazards. For example - Water that gets collected over the ground acts as a breeding ground for mosquitoes and many other unwanted organisms causing the smell and spread of infections.

## BLOCKERS

Several things, such as high cost, and lack of compatibility between the bot and plumbing system, may make it difficult for users to fulfill their requirements for Pipe Inspection.

# PROJECT SCOPE

## PROJECT RESULTS

Following are some of the outcomes we aim to achieve for our project:

1. Designing a suitable experiment that can help us to understand the performance of our selected sensors and what parameters are used for the same.
2. Comparison of the performance of the different sensors being tested, including any differences in sensitivity, resolution, or response time.
3. Recommendations for the use and application of the sensors based on the results of the testing.
4. If the right sensors and parameters are found, test them in the smart ball (end product) itself.

## ASSUMPTIONS

Depending on the project's goals and objectives, we have made several assumptions when developing our experimental setup to evaluate passive acoustic sensors and pressure sensors. Some such presumptions that would need to be taken into account are as follows:

1. The sensors being tested are functioning correctly and have been properly calibrated or adjusted.
2. The testing environment is stable and controlled, with minimal variations in temperature, humidity, or other factors that might affect the performance of the sensors.
3. The data being collected is accurate and representative of the conditions being tested.
4. The results of the testing will be representative of the performance of the sensors under normal operating conditions.

## STAKEHOLDERS

1. **Pipe Inspection Companies:** Will use the robots to perform inspections of pipes for their clients, to identify and address issues such as corrosion, blockages, or leaks, and to inspect hard-to-reach or hazardous areas.
2. **Pipeline Operators:** Will perform inspections using robots to identify any issues that may affect the flow of materials and provide accurate and reliable data about the condition of the pipes.
3. **Government Agencies:** These agencies will employ these technologies to inspect pipes for water or sewage systems, or to inspect other types of infrastructure such as pipelines or oil and gas facilities
4. **Industrial Users:** Employ to inspect pipes in their facilities for a variety of purposes, ensuring the safety and reliability of their operations, and complying with regulations.

## MARKET SURVEY

| Aspects | Details |
|---|---|
| BY ROBOT TYPE | 1. **Stationary Robot Arm**<br>2. **Mobile Robots** |
| BY TESTING TYPE | 1. **Automated Metrology**<br>2. **Non-Destructive Inspection** |
| BY END-USER INDUSTRY | 1. **Oil & Gas**<br>2. **Food & Beverage**<br>3. **Pharmaceutical**<br>4. **Electronics** |
| BY REGION | 1. **North America** (US, Canada, Mexico)<br>2. **Europe** (Germany, France, Italy, Spain & the Rest of Europe)<br>3. **Asia-Pacific** (China, India, Japan, South Korea & Rest of Asia-Pacific)<br>4. **LAMEA** (Latin America, Middle East, Africa) |
| KEY MARKET PLAYERS | 1. **Eddyfi Technologies**<br>2. **Gecko Robotics, Inc** |

| | |
|---|---|
| | 3. **Genesis Systems (IPG Photonics)**<br>4. **Honeybee Robotics**<br>5. **Invert Robotics**<br>6. **JH Robotics, Inc**<br>7. **Montrose Technologies**<br>8. **Shenzhen SROD Industrial Group Co Ltd,**<br>9. **Universal Robots**<br>10. **Waygate Technologies (Baker Hughes Company)** |

**Source:** Pipe Inspection Robot Forecast Growth Study - (2021-2030) via Allied Market Research
https://www.alliedmarketresearch.com/inspection-robots-market-A08254

## USER NEEDS LIST

| Users | User Need | Importance Level |
|---|---|---|
| **All Users** | Ability to inspect pipes of different diameters | High |
| **Pipe Inspection Companies** | Ability to navigate through with bends and turns | High |
| **Pipeline Operators** | High-resolution camera for detailed inspection | High |
| | Built-in lighting for clear visibility | High |
| **Government Agencies** | Remote control for real-time monitoring | High |
| **Industrial Users** | Ability to handle different types of pipes (e.g. PVC, steel, etc.) | Moderate |
| | Long battery life for extended use | Moderate |
| | Ease of use and maintenance | Low |

# SECTION 2: PRODUCT DEVELOPMENT

## PRODUCT USAGE CONTEXT

### TECHNOLOGICAL LIMITATIONS

There are several technical limitations to consider when using a persistent-monitoring pipe inspection robot:

1. **Size and Shape Constraints:** The robot may be limited in its ability to navigate through small or irregularly shaped pipes.

2. **Battery Life:** The robot may be limited in its ability to operate for long periods, depending on its battery life. This could limit its ability to perform comprehensive inspections.
3. **Sensors and Data Collection:** The robot's sensors and data collection capabilities may be limited, which could impact its ability to accurately assess the condition of the pipes it is inspecting.
4. **Communication:** The robot may be limited in its ability to communicate with external systems, which could impact its ability to transmit data or receive instructions.
5. **Durability:** The robot may be prone to wear and tear or damage during its inspections, which could impact its reliability and lifespan.

## SPECIFICATIONS

| Specifications | User Needs | Importance |
|---|---|---|
| It should be small enough to fit through the pipes, but also large enough to carry the necessary components. | Ability to inspect pipes of different diameters | High |
| Able to move through the pipes in a controlled & stable manner. | Ability to navigate through with bends and turns | High |
| Equipped with sensors and cameras that can provide detailed information about the condition of the pipes | High-resolution camera for detailed inspection | Moderate |
| Withstanding moderately harsh conditions, including warm temperatures, corrosive materials, and mechanical stress. | Ability to handle different types of pipes (e.g. PVC, steel, etc.) | Moderate |
| A reliable power source, such as a battery or tethered source, to allow it to operate for extended periods. | Long battery life for extended use | Low |
| The robot should be easy to maintain, with easily accessible components that can be quickly replaced if necessary. | Ease of use and maintenance | Low |

# RESEARCH

## INITIAL RESEARCH

1. Many different factors need to be considered when designing a pipe inspection robot, including the type of pipeline that the robot will be inspected, the size and shape of the robot, and the sensors and sensor systems that the robot will use to gather data about the pipeline's condition.
2. One of the key aspects of the research on pipe inspection robots is the concept design of the robot. This involves developing a detailed plan for the robot's overall design and functionality, taking into account the specific requirements and constraints of the inspection task at hand.
3. many different approaches can be taken when designing a pipe inspection technology. It can be done using sound, X-ray, and many other methods both by working over the ground and under the ground as well.
4. In addition to the size and shape of the robot, the concept design of a pipe inspection robot may also include other features such as locomotion systems, control systems, and communication systems. The locomotion system is responsible for propelling the robot through the pipeline, while the control system is responsible for managing the robot's movements and actions. The communication system is used to transmit data and other information back and forth between the robot and a remote operator or control system.
5. The concept design of a pipe inspection robot is a critical step in the overall process of designing and building these robots, as it sets the foundation for the final design of the robot. Once the concept design has been completed, the next step is to build a prototype of the robot and conduct testing and validation to ensure that it is capable of performing its inspection tasks effectively and efficiently.

6. Overall, the research of pipe inspection robots and the concept design of these robots is an ongoing process that involves several steps and considerations, including the type of pipeline that the robot will be inspected, the size and shape of the robot, and the sensors and sensor systems that the robot will use to gather data about the pipeline's condition. By carefully researching and designing these robots, engineers and researchers can ensure that they can effectively and efficiently perform their inspection tasks.

**PROJECT RESOURCE - ARTICLES**

We researched extensively to understand how greatly industries are affected due to pipe leakages. We found a large number of articles mentioning the extent of the problem we are trying to resolve and an even greater number of papers trying to tackle this problem.

This is a journal article that talks about pipe leakages and the problems it causes:

1. **Leak detection in water distribution networks:** Leak detection in resource transmission pipelines is an important area of research because leaks in the water transmission industry can lead to significant losses of water and financial and social costs. Leaks can also pose hazards as they can grow and introduce contaminants or pathogens into the network. Water transmission pipelines can lose an average of 20-30% of the water transmitted through them, and this loss can be higher in older systems with inefficient maintenance. Causes of water loss in transmission pipelines include leakage, metering errors, public usage, and theft. Leaks are estimated to contribute about 70% of water loss in water transmission systems, and this percentage is expected to be higher in poorly managed networks. Gas pipeline leaks can be more hazardous and costly than water leaks. In the UK, the monetary impact of leak repairs is estimated to be around £7 billion annually, with indirect damage costs of £1.5 billion and social impact costs of £5.5 billion.

Below is a news article highlighting that leaks in water pipes placed underground are left unattended until they cause major damage. Our robot is the solution to all such problems.

2. **Leakage in underground water pipelines damaging roads:** Water leaks from pipes under the roads are causing significant damage in various parts of the city of Chandigarh. These leaks fill potholes with water and can also cause damage to stormwater drainage systems, electricity cables, and telephone cables, which requires the entire road to be dug up. This causes inconvenience to residents and increases expenditure. Many roads in the city are being repaired, but roads near roundabouts have potholes filled with water due to ongoing leaks in the pipes. These leaks are often only noticed when the roads are damaged.

**COMPONENTS**

1. PASSIVE ACOUSTIC SENSORS

   Passive acoustic sensors are sensors that are designed to detect and amplify sounds that are produced by a system or process. They are often used to monitor the condition of machinery or infrastructure, such as pipes, to detect cracks or leaks.

   In a pipe monitoring system, the pipe robot equipped with passive acoustic sensors is used to navigate through the pipes and listen for any sounds that might indicate a problem. The sensors are typically mounted on the robot's body or internally in a water-tightened chamber close enough to perceive the leaks.

   The proximity range of passive acoustic sensors is typically determined by the sensitivity of the sensors and the strength of the sound is detected. In general, passive acoustic sensors are sensitive enough to detect sounds at a distance of a few centimeters to a few meters, depending on the specific design of the sensor and the intensity of the sound being detected.

This is the pick for our robot as it's efficient, cost-effective, and easy to deploy in the robot.

2. GOMBOC

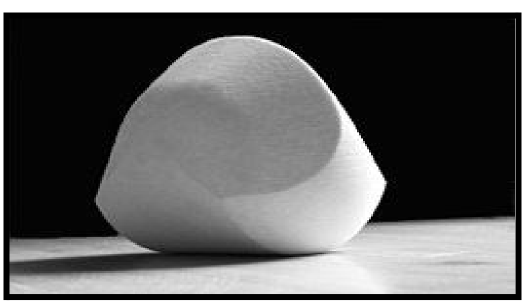
The Gömböc is a unique mathematical shape that is characterized by having just one stable and one unstable point of equilibrium. This means that no matter how it is oriented, it will always come to rest with a specific side facing upwards.

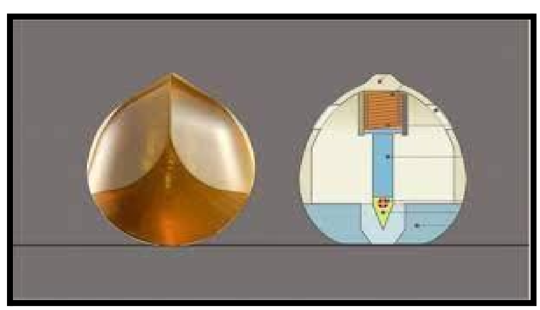
One of the key specialties of the Gömböc shape is its ability to roll without slipping. This is due to the shape's unique geometry, which causes it to roll in a straight line when it is given a slight push.

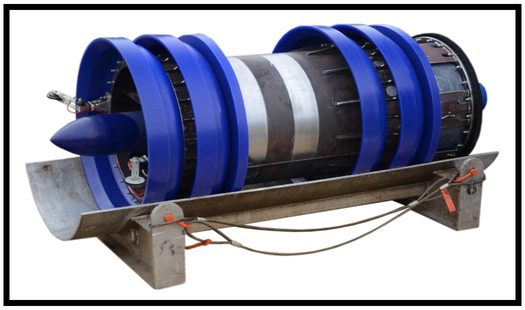
Another specialty of the Gömböc is its ability to write itself regardless of its orientation. This makes it a self-righting object, which is useful in a variety of applications. Specifically in our use case, it's a boon as our robot needs to maintain a stable position on the uneven surface of the water.

The Research was mostly focused on understanding the ways to implement the robot. Hence, the Robot's Body - Gömböc and the Sensor - Passive Acoustic Sensor give an overall understanding of the robot.

**CONCEPT DESIGN (INSPIRATION)**





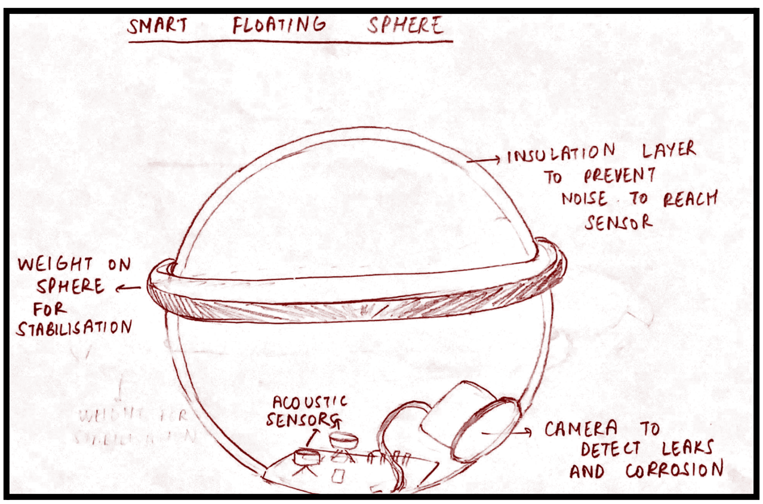


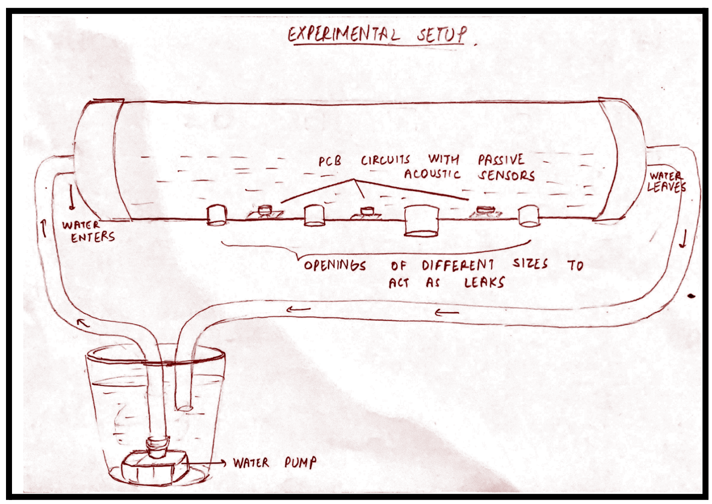
## SECTION 3: PROTOTYPE & DESIGN

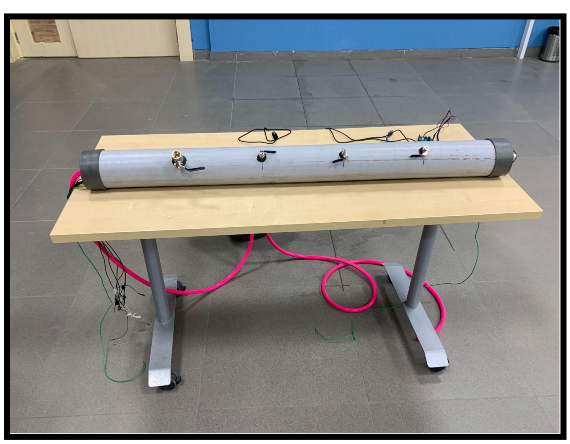
# PROTOTYPE

### PROTOTYPE'S PURPOSE

1. The prototype is an experimental setup (right picture) that is being used to test the performance of sensors that will be put in the final robot. (left picture)



2. Some sensors are inside this pipe whose waveform will be tested to see when water is flowing in the pipe. The aim is to identify and differentiate waveforms in different cases - no leaks, one leak (of different sizes), and more.
3. Use of endoscopic camera will be used to act as a confirmatory test, this camera will check for bubbles that according to our assumption must be observed in case of a leak.
4. After these sensors are tested chosen and calibrated they will be put in this ball which will again be deployed in the pipe.
5. the shape of This ball would be tested using differently shaped - one of a gomboc and one of a sphere. A floating disc attached to the ball's surface would presumably act as a stabilizing unit that will control the wobble of this ball.
6. This ball will also be insulated on the top to protect the sensors from noisy vibrations from the pipe.
7. Once the prototype has been thoroughly tested and validated in the future, it may be used as the basis for the design of the final version of the robot, which will be deployed in the field to perform inspections on real pipelines. Overall, the purpose of a persistent pipe inspection robot's sensor experimental setup prototype is to ensure that the robot is equipped with the necessary sensors and sensor systems to accurately and reliably gather data about the condition of pipelines and to test and validate the overall design of the robot to ensure that it is capable of performing its inspection tasks effectively and efficiently.
8. The data collected from this testing would then be fed into a neural network to generate classifications for different cases of sound waves.

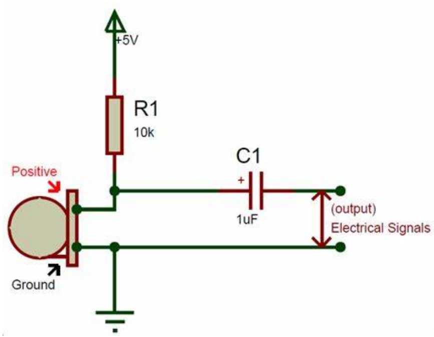
## PROTOTYPE'S FABRICATION

1. The fabrication of a persistent pipe inspection robot's sensor experimental setup prototype and the robot design involves several steps and processes, ranging from the initial conceptualization and design of the robot to the final assembly and testing of the prototype.

2. The first step in the fabrication process is the conceptualization and design of the robot. This involves creating detailed drawings and diagrams, as well as identifying the specific sensors and sensor systems that will be used on the robot.

3. The next step was to build the experimental setup. The materials and parts that were used are as follows:

    - 4 Ft pipe, diameter - 4 inches
    - Valves - 3 of diameter 0.8cm and 1 of diameter 2 cm
    - Endoscopic Camera
    - 3 PCBs each with the following:
        - 3 - Passive Acoustic Sensors
        - 3 - 10 kΩ Resistors
        - 3 - 1µF capacitors
        - Given below is the circuit diagram for the PCB used.




- 18W Motor Pump
- Water Reservoir
- 10 ft hose pipe of diameter 0.5 inch
- Pipe Caps
- Dowsil Silicone Sealant 732, 734
- M-Seal
- Soldering Station and material
- Electric Wires (insulated)
- Arduino Uno board
- Electric Tape
- Jumper wires
- Teflon tape
- Scale
- Pipe rubber nipples

The experimental setup was assembled in the following manner:

1. Three holes were drilled into the caps. First of about 0.55 inches in diameter at the center, the second of about 0.75 cm, and the third of about 2 cm in diameter. The second and third were

made along the circumference of the cap. Rubber nipples were attached in the center holes using silicon sealant and final waterproofing using M Seal.

2. After making the PCBs following the diagram above, they were made waterproof using silicon sealant.
3. Long wires were then soldered to these PCBs
4. 4 holes were made in the pipe, and the valves were wrapped with Teflon tape to make sure they fit tightly in the hole. After being inserted in the holes, the valve insertion holes were waterproofed using M Seal.
5. All the PCBs were tightly wrapped on a long scale which was then put into the pipe and stuck next to the openings of the valves using a silicon sealant.
6. The endoscopic camera was put inside and its controlling wires were passed from the holes made in the pipe cap.
7. The wires were taken out marked and the caps were closed. The hose was then connected to the pump and water was circulated in the pipe. Sensors were connected to Arduino UNO and using serial plotter was used to see the waveform of sensors when the valves were closed and when they were open.  The code for the Arduino is given below.
8. The endoscopic camera was then used to find bubbles and the flow of water in the pipe during testing.

```
void setup() {
  Serial.begin(500000);
}

void loop() {
  //int y1 = analogRead(A0);
  Serial.print(analogRead(A0));
  //Serial.print(",500,510");
  Serial.println();
}
```

4. The shape and outer cover of the robot body were 3D printed to observe its behavior in water concerning its stabilization capabilities

**PROTOTYPE'S SOFTWARE SIDE**

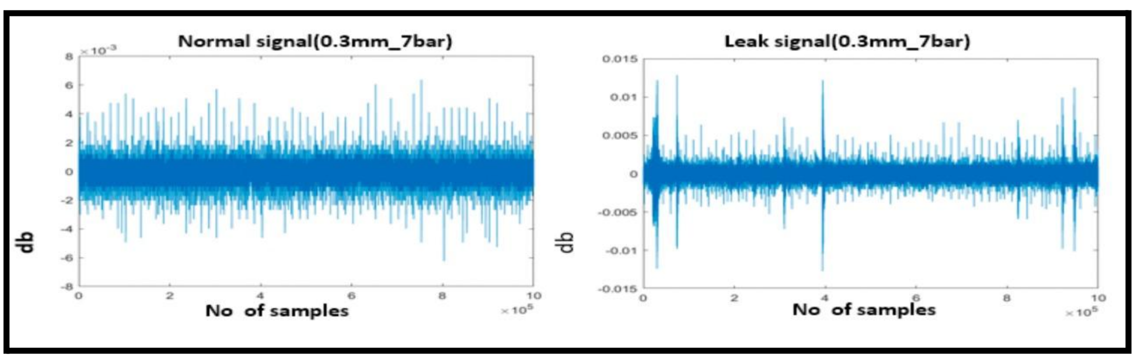
1. **Data Collection:** The first step in implementing a neural network for leakage classification is to collect the necessary data. In this case, data from acoustic sensors can be used to detect leaks and water flow in cracks. The data should be collected in a controlled environment to ensure that it accurately reflects the conditions that the neural network will be used.

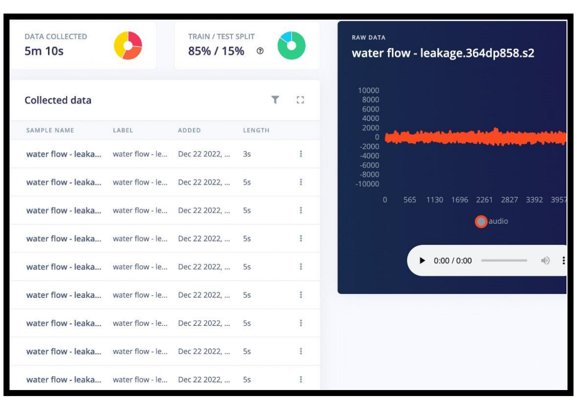
2. **Data Simulation:** In some cases, it may not be possible to collect real-world data for leakage classification. In such cases, it is possible to simulate the data that would be collected from acoustic sensors under different conditions (e.g. different levels of water flow or different types of leaks). This simulated data can then be used to train and test the neural network.

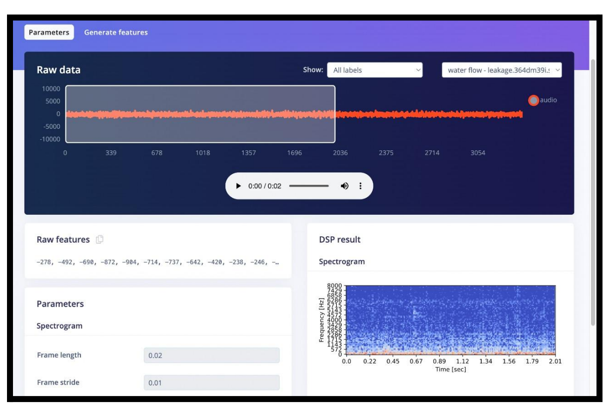
3. **Data Preparation:** Once the data has been collected or simulated, it should be divided into training, validation, and testing sets. The training set is used to train the neural network, the validation set is used to tune the model's hyperparameters, and the testing set is used to evaluate the final model's performance.

4. **Feature Engineering:** To feed the data into a neural network, it must be transformed into a feature vector. One way to do this is to create a spectrogram of the data, which represents the frequency spectrum of the acoustic signal over time. This spectrogram can then be used as the feature vector for the neural network.
5. **Neural Network Architecture:** Once the data has been prepared and transformed into a feature vector, a neural network can be created using a library such as Keras or TensorFlow. The specific architecture of the neural network will depend on the characteristics of the data and the desired classification performance. For example, a convolutional neural network (CNN) may be well-suited for this task due to its ability to learn spatial patterns in data.

6. **Training and Evaluation:** Once the neural network has been created, it can be trained using the training data and optimized using the validation data. The final model can then be evaluated using the testing data to determine its performance on unseen data.

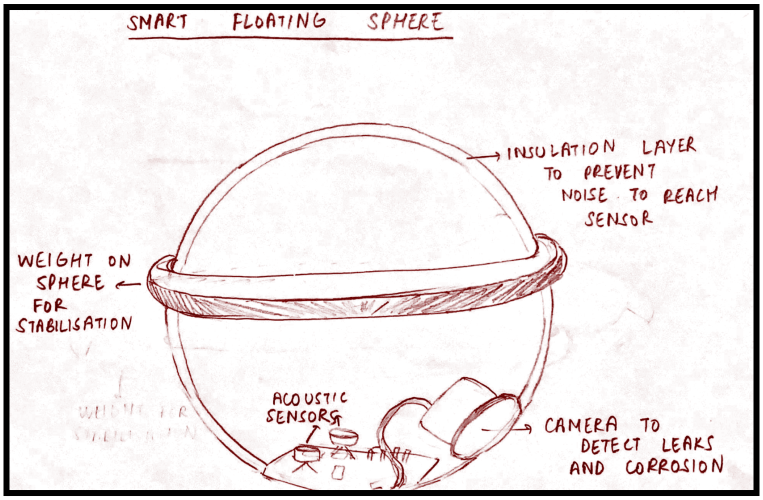


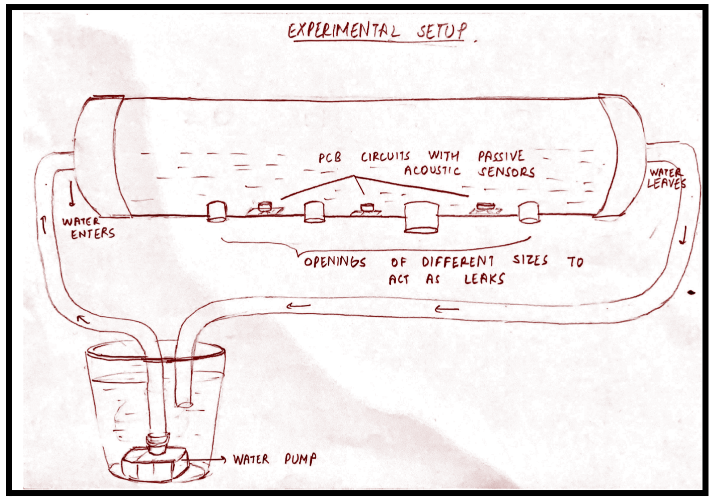



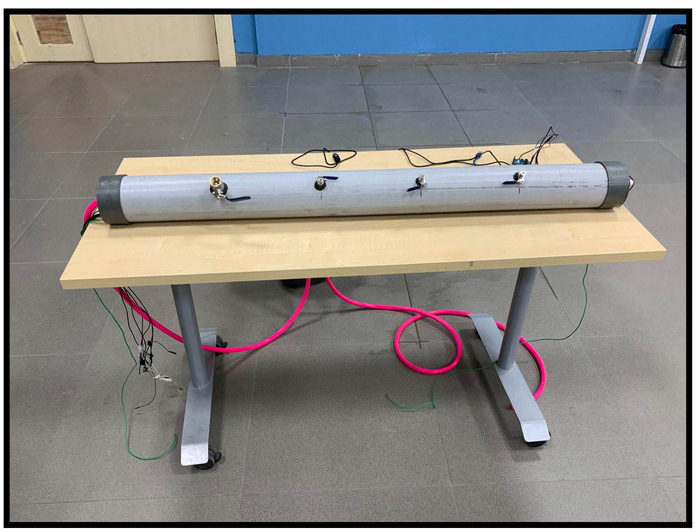
## PROTOTYPE RENDERINGS

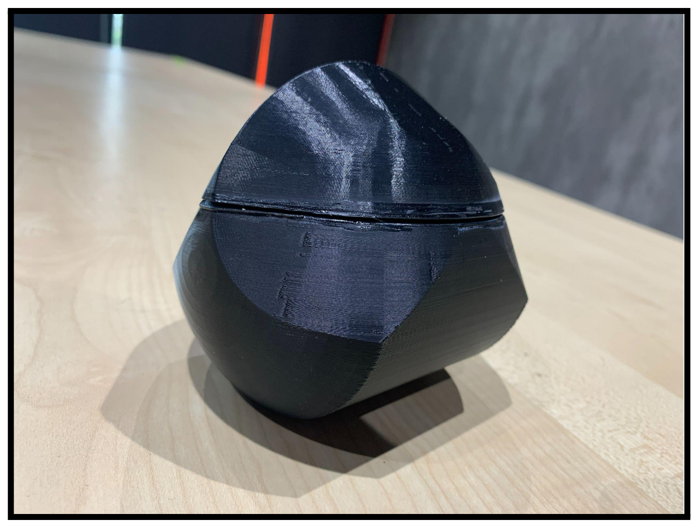
### DRAWINGS




### EXPERIMENTAL SETUP and GOMBOC DESIGN





## SECTION 4: TESTING & FUTURE

## VALIDATION

| Specifications | User Needs | Importance | Verify |
|---|---|---|---|
| It should be small enough to fit through the pipes, but also large enough to carry the necessary components. | Ability to inspect pipes of different diameters | High | ✗ |
| Able to move through the pipes in a controlled & stable manner. | Ability to navigate through with bends and turns | High | ✓ |
| Equipped with sensors and cameras that can provide detailed information about the condition of the pipes | High-resolution camera for detailed inspection | Moderate | ✓ |
| Withstand harsh conditions, including warm temperatures, corrosive materials, and mechanical stress. | Ability to handle different types of pipes (e.g. PVC, steel, etc.) | Moderate | ✓ |
| A reliable power source, such as a battery or tethered source, to allow it to operate for extended periods. | Long battery life for extended use | Low | ✓ |
| The robot should be easy to maintain, with easily accessible components that can be quickly replaced if necessary. | Ease of use and maintenance | Low | ✓ |

## SECTION 5: WHAT's NEXT?

### PIPE MONITORING & REPAIRING ROBOT

A pipe monitoring robot equipped with passive acoustic sensors that can also repair pipes would be a useful tool for maintaining and repairing pipes in a variety of industries, including oil and gas, water and wastewater, and construction. To design such a robot, it would be necessary to consider the specific requirements of the application, including the size and shape of the pipes to be monitored and repaired, the materials of the pipes, and the environment in which the robot would be used. The robot would need to be equipped with passive acoustic sensors that can detect sounds produced by cracks or leaks in the pipes, as well as other sensors and cameras to provide a comprehensive view of the condition of the pipes.

In addition to the sensors, the robot would need to be equipped with a range of repair tools, such as a welding torch, a pipe cleaning tool, or a pipe lining tool, depending on the specific repair work required.

The robot would also need to be able to navigate through the pipes and maneuver in tight spaces, as well as be able to withstand the harsh conditions often found in pipes, such as high pressure, temperature fluctuations, and corrosive materials. The robot would also need to be equipped with machine-learning algorithms that can analyze the data collected by the sensors in real time and identify patterns that might indicate the early stages of a leak or crack. These algorithms would need to be trained on a large dataset of previous leaks and cracks so that they can learn to recognize the early warning signs of a problem.

Once the robot has identified a potential problem, it can transmit this information back to a control center, where it can be analyzed and used to plan a repair. The robot could then be equipped with the appropriate repair tools and sent back into the pipes to carry out the repairs before the leak or crack becomes a more serious issue.

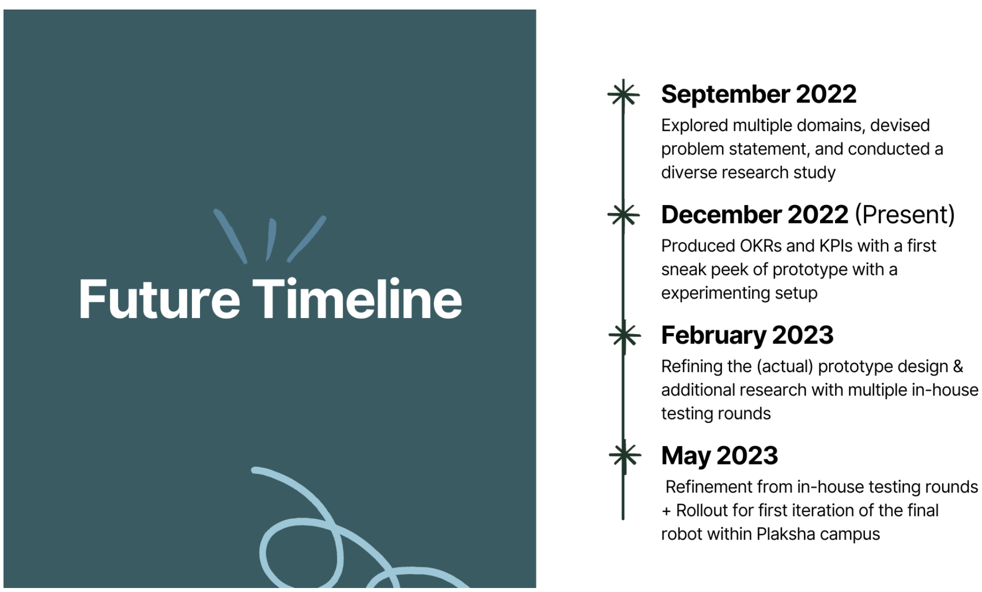
Overall, a pipe monitoring robot with passive acoustic sensors that can repair pipes would be a valuable asset for a wide range of industries, allowing for efficient and cost-effective maintenance and repair of pipes without the need for human intervention.

### ANY PIPE FIT - PIPE MONITORING ROBOT

First and foremost, the robot would need to be small and highly maneuverable, so that it can fit into pipes of any size and shape. This might involve using a flexible or articulated design, or incorporating features such as telescoping arms or cameras that can be extended to reach tight spaces. The robot would also need to be equipped with a range of sensors and cameras to provide a comprehensive view of the condition of the pipes. This might include passive acoustic sensors for detecting sounds produced by cracks or leaks, as well as other sensors such as pressure gauges, temperature sensors, and corrosion sensors.

In addition to the sensors, the robot would need to be equipped with a range of repair tools, such as a welding torch, a pipe cleaning tool, or a pipe lining tool, depending on the specific repair work required. Finally, the robot would need to be able to navigate through the pipes and maneuver in tight spaces, as well as be able to withstand the harsh conditions often found in pipes, such as high pressure, temperature fluctuations, and corrosive materials. Overall, a pipe monitoring robot that can fit into any pipe would be a valuable asset for a wide range of industries, allowing for efficient and cost-effective maintenance and repair of pipes without the need for human intervention.

## FUTURE TIMELINE




## UN-SDGs addressed in this project are-

**11 sustainable cities and communities**

**9 industry innovation and infrastructure**

## 6 clean water and sanitation

## LEARNING OUTCOMES

1. Understanding the principles of passive acoustic sensors and how they can be used to detect and locate sounds or vibrations within pipes. P10 - components
2. Knowledge of the capabilities and limitations of endoscopic cameras and how they can be used to inspect the inside of pipes. p10
3. Experience in programming to make a model for collecting and storing data, analyzing it, and visualizing the required results. p16
4. Developing skills in data analysis and interpretation, including the ability to analyze and interpret data collected by the sensors and camera to identify problems or abnormalities within the pipe. p17-18
5. Experience in working as part of a team to plan, execute, and report on a technical project, including the ability to communicate technical concepts to a non-technical audience. We all shared tasks and ideated together. p1
6. Examine societal and individual needs  p3, p5
7. Take initiative in working in team p1
8. Convey engineering solutions in terms of value addition and salient features p13 - p14
9. Learned to apply creative thinking to ambiguous problems p13 - p14
10. Learned to apply systems thinking to complex problems p13-p14

## BIBLIOGRAPHY

[1] S. El-Zahab and T. Zayed, "Leak detection in water distribution networks: an introductory overview," *Smart Water*, vol. 4, no. 1, Jun. 2019, DOI: 10.1186/s40713-019-0017-x.

[2] “Leakage in underground water pipelines damaging roads,” *The Indian Express*, Jun. 23, 2009. https://indianexpress.com/article/cities/chandigarh/leakage-in-underground-water-pipelines-damaging-roads/ (accessed Dec. 25, 2022).

[3] A. Lockwood, T. Murray, G. Stuart, and L. Scudder, “Locating leaks from water supply pipes using the passive acoustic method,” *Journal of Water Supply: Research and Technology-Aqua*, vol. 54, no. 8, pp. 519–530, Dec. 2005, DOI: 10.2166/aqua.2005.0046.

[4] J. Liu, M. Rhodes, and A. Rahman, “Passive acoustic wave sensor system,” Jun. 17, 2005

[5] N. Kishor Banjara, S. Sasmal, and S. Voggu, “Detection of Leakage in Pipelines using Passive Acoustic Emission Technique.” Accessed: Dec. 25, 2022. [Online]. Available: https://www.ndt.net/article/nde-india2019/papers/CP181.pdf

[6] “Gömböc—The Shape That Shouldn’t Exist,” *www.youtube.com*, Jul. 12, 2020. https://www.youtube.com/watch?v=rvVF5QWSYF4&t=209s (accessed Dec. 25, 2022).

[7] S. Gupta, “Simple Microphone to Speaker Amplifier Circuit,” *Circuit Digest*, Nov. 13, 2018. https://circuitdigest.com/electronic-circuits/simple-microphone-to-speaker-circuit

[8] W. Drevo, “worldveil/dejavu,” *GitHub*, Dec. 09, 2020. https://github.com/worldveil/dejavu

[9] “Pipe Repair Methods: How to Repair Leaks in Water Lines,” Oct. 06, 2020. https://www.advancedfrpsystems.com/pipe-repair-methods/

[10] “SmartBall - Leak and Gas Pocket Detection - Pure Technologies,” *Pure Technologies*, 2016. https://puretechltd.com/technology/smartball-leak-detection/

[11] Y. Qu, P. Durdevic, and Z. Yang, “Smart-Spider: Autonomous Self-driven In-line Robot for Versatile Pipeline Inspection * *The authors would like to the support from Danish Hydrocarbon Research and Technology Centre(DHRTC) through DHRTC Radical Project Programme,” *IFAC-PapersOnLine*, vol. 51, no. 8, pp. 251–256, 2018, DOI: 10.1016/j.ifacol.2018.06.385.

[12] “Finding leaks while they’re easy to fix,” *MIT News | Massachusetts Institute of Technology*. https://news.mit.edu/2017/robot-finds-leaks-water-pipes-0718

[13] “MRINSPECT ( Multifunctional Robotic crawler for In-pipe inspection) series,” *www.youtube.com*, Spring 16, 2016. https://www.youtube.com/watch?v=h6dYc0yfXQc (accessed Dec. 25, 2022).

[14] A. Nayak and S. K. Pradhan, “Design of a New In-Pipe Inspection Robot,” *Procedia Engineering*, vol. 97, pp. 2081–2091, Jan. 2014, doi: 10.1016/j.proeng.2014.12.451.

[15] D. Wiley, “How Does Internal Pipe Coating Work?,” *NuFlow Midwest*, May 22, 2019. https://www.nuflowmidwest.com/how-does-internal-pipe-coating-work/