CBI4AI 2024

Final Report - The Pipers

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Executive Summary

Nanoplumbr is a fully autonomous robot that can be deployed inside any pipe to temporarily seal water leakages. It is specially relevant in situations where propper fixing is delayed, where it can help save big amounts of water. Nanoplumbr facilitates a quick response to new leaks thanks to a very simplified deployment process, and it is capable of operating without the need to cut the water supply to the affected area. The robot can be recovered and reused by repair professionals when they eventually access and fix the pipe.

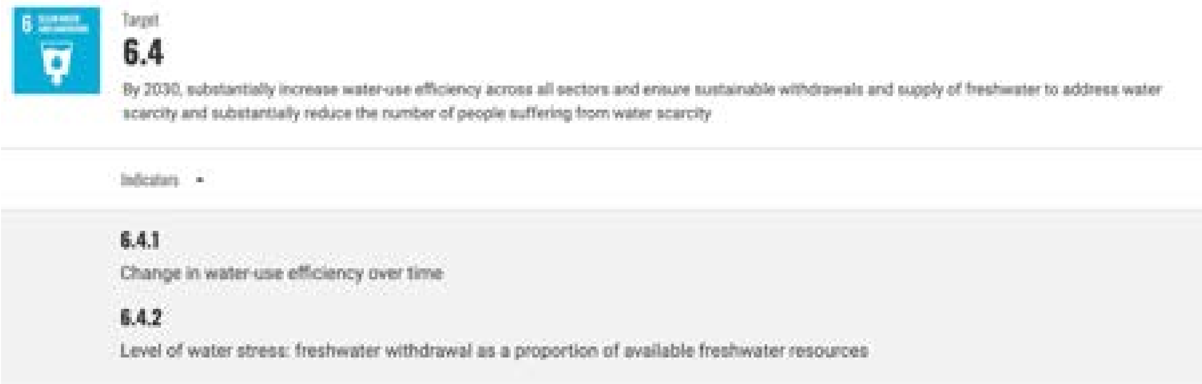
Research Question

How might we temporarily and quickly fix pipe leakages in the main water distribution pipes for Agües de Barcelona in order to minimize water loss in the main water distribution pipes?

Introduction

Understanding SDG 6.4

SDG target 6.4 emphasizes the urgent need to substantially increase water-use efficiency across all sectors by 2030. This goal aims to ensure sustainable withdrawals and supply of freshwater, addressing water scarcity and reducing the number of people suffering from it. Achieving this target involves improving the management and use of water resources, recognizing that water scarcity is a growing challenge globally.


Target

6.4

By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity

Indicators

6.4.1

Change in water-use efficiency over time

6.4.2

Level of water stress: freshwater withdrawal as a proportion of available freshwater resources

Inefficient Water Use

Inefficient water use is prevalent in various sectors, contributing significantly to water losses and highlighting the need for targeted solutions. In agriculture, traditional irrigation methods such as flood irrigation lead to significant water wastage due to evaporation and runoff. Industrial processes often involve water-intensive activities without adequate recycling and reuse measures. Domestic water use also faces inefficiencies due to outdated plumbing fixtures and wasteful practices. Urban infrastructure, especially aging water systems, results in substantial water losses due to leaks. These inefficiencies contribute to water losses through leakages in poorly maintained water distribution systems, evaporation in agricultural settings, and runoff and seepage in inefficient irrigation systems.

Research & Ideation

Organizing our Research

After broadly examining the Sustainable Development Goals (SDG) and the role of water in society and the environment, we decided to structure our research to better prepare for the upcoming ATTRACT technologies in the following way:

This way, once the technologies were published, it would be easier for us to evaluate for which problems the technologies could potentially be implemented and decide on the problem.

Deciding on the Problem

Upon the introduction of the technologies, our immediate goal was to identify a pertinent problem to address. Initially, we were heavily focused on the technologies themselves and their possible applications, which slowed our progress in problem identification as we were working backwards from solution to problem. To correct our course, we shifted our strategy:

1. Each team member was tasked with identifying impactful problems.

2. They would then explore existing or conceive new solutions, potentially incorporating one of the ATTRACT technologies.
3. Finally, they prepared a pitch for what they believed was the most viable problem-solution pair, backed by compelling arguments.

Rather than a generalized approach, we decided it was more effective for each individual to focus on ideas they were particularly passionate about. This approach made the research process require less effort in terms of motivation, as everyone was inherently motivated to conduct thorough research and create an impressive pitch for their own ideas.

Our findings covered a range of issues, 1) household water use inefficiencies and reuse possibilities, or 2) inefficient water use in agriculture and the irrigation methods, or 3) the textile industry water consumption and wastewater reutilization to 4) pipe leakages and their detecting and fixing approaches. In hindsight, even this approach trying to reverse the order of solution-problem to identify the problem was too logical and focused too much on the solution. We still thought too much about if we will find a solution to the problem, before deciding on the problem. We wanted to be sure to not be stuck with a problem we cannot solve. In this regard, we were quite risk-averse and hesitant to decide. However, through this approach and the critical thinking employed, we were also able to identify a lot of core problems and a lot of solutions and this research which gave us a more thorough (to be fair also biased) perspective to vote on a problem-solution pair.

Ultimately, the pitches helped us converge on the issue of water pipe leakages. It was not only the problem-solution pairing but the alarming severity of the issue itself that guided our final decision.

Water Pipe Leakages as our Problem

Approximately 25% of Europe's water distributed through pipes is lost annually due to leakages. Italy, for example, experiences an average loss of about 40% due to the same issues. And since we have around 740 million inhabitants in Europe, with each consuming around 100 liters a day, around 27,000 gigaliters of water is consumed per year in Europe. Assuming that all of this water goes through the water distribution pipes, 6,500 gigaliters of water is lost each year in Europe just because of pipe leakages. That is almost 10 times the capacity of all inner reservoirs in catalunya. Additionally, assuming that the average price per cubic meter is 2 Euro, this lost water is equal to almost 14 billion euros. That is four times the annual budget of Barcelona of 2023. Initially unaware of the severity of this issue and the inefficiency in water distribution, we chose to delve deeper into this problem.

We quickly differentiated between detecting leaks and fixing them, and decided to concentrate on detection. This decision was primarily based on the somewhat arbitrary belief that detection is presenting a more significant challenge and potentially having a greater impact.

Given the global prevalence of this problem, we decided to initially focus our efforts on Barcelona to manage the complexity and scope of our research effectively.

Reasons for Picking Barcelona

1. Environmental Challenges and Local Conditions

Droughts and Water Scarcity

Barcelona regularly experiences severe drought conditions that significantly impact its water resources. The urgency of these conditions demands innovative solutions to enhance water conservation. In this context, our project can contribute effectively by identifying and mitigating water loss, thereby alleviating the critical shortage. Implementing advanced leakage detection technologies in Barcelona offers a meaningful opportunity to make a significant impact on the community by conserving scarce water supplies.

Geographical and Climatic Challenges

The unique geographical and climatic features of Barcelona, typical of many Mediterranean coastal cities, present specific challenges in water management. These include variable rainfall patterns and high seasonal tourist influxes, which exacerbate water scarcity. Addressing these specific challenges in Barcelona can provide valuable insights and scalable solutions applicable to other regions with similar conditions.

2. Innovation and Supportive Framework

Innovative Ecosystem

Barcelona's water management sector has shown a readiness to adopt innovative solutions, particularly in tackling issues like pipe leakages. In the past, local water suppliers have experimented with various technologies to improve their systems. This historical openness not only suggests a high likelihood of support for new initiatives but also means that the local infrastructure and professional expertise are likely in place to facilitate quick implementation and testing of our project. This environment enables faster progression from proof of concept to widespread adoption.

Regulatory Support

The local government in Barcelona provides robust support for environmental and sustainability initiatives through incentives and a supportive regulatory framework. These policies are designed to encourage the adoption of innovative technologies and practices, reduce barriers to implementation, and foster a culture of sustainability. This support is crucial for ensuring the seamless integration of new solutions into existing infrastructures and for accelerating the broader acceptance and effectiveness of our project.

3. Community Involvement

Public Engagement

Barcelona boasts a strong sense of community engagement with a keen interest in environmental sustainability. The local population is generally well-informed about the issues of water management and is supportive of initiatives aimed at improving these systems. By leveraging this community interest, our project can enhance public acceptance and encourage participatory approaches, ensuring that the solutions developed are not only technically effective but also socially embraced.

Researching and Deciding on Solution instead of Narrowing down the Problem

Following our initial assessment, we crafted a preliminary "How Might We" statement:

"How might we detect leakages for Aigües de Barcelona in order to minimize the resulting water loss from undetected main water distribution pipes?"

However, we soon encountered an oversight. Believing our problem was sufficiently defined and acknowledging its significance, we prematurely shifted our focus to solutions. A more thorough refinement of the problem at this stage would have been more efficient. Moreover, we relied too much on our prior research on solutions. As a result, we found ourselves focusing too much on the state-of-the-art technologies for leak detection that we had previously studied, while we tended to overlook more creative and innovative problem-solving ideas that could arise spontaneously or intuitively.

We delved deeper into several technologies:

1. Ground Penetrating Radar (GPR), an electromagnetic technique that, according to studies conducted up to 2020, is highly effective in detecting underground pipe leakages.
2. Aerial thermal imaging combined with artificial intelligence, presumed to be even more efficient.
3. The use of Pipeline Inspection Gauges (PIGs) that are inserted into pipes to detect leaks
4. The application of helium gas for similar detection purposes

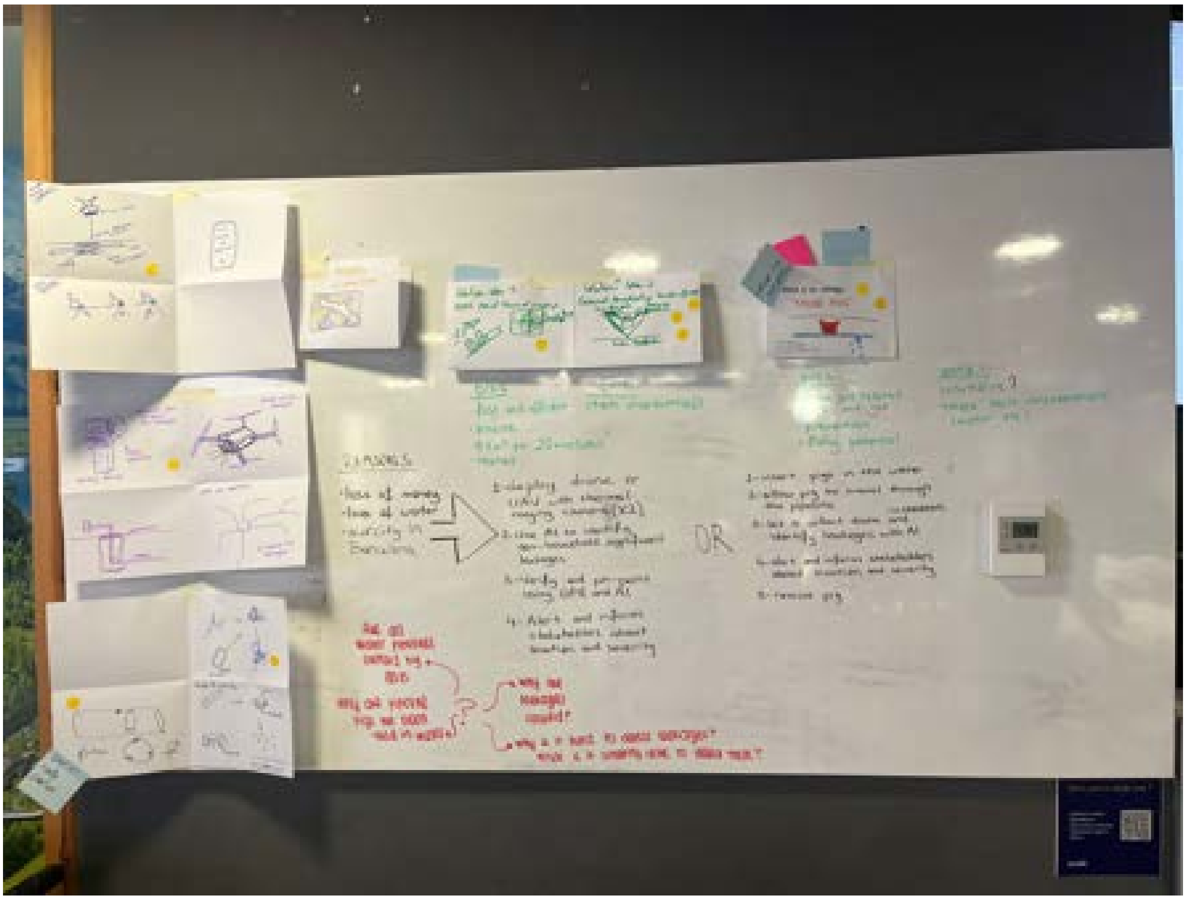
We were quite enthusiastic about the usage and possibilities of this technology. For instance, we discussed leveraging aerial thermal imaging with UAVs/drones to survey large areas quickly, followed by a more precise confirmation using GPR.

To visualize and further develop our ideas, each team member sketched four different approaches to address the leakage detection issue, drawing out potential solutions and how they tackle the issue:

The individual solutions had some overlaps unfortunately, as we have been discussing the currently employed/tested technologies and their potential as a solution right before this step. Nevertheless we then narrowed this solution set down to the most promising two solutions from the drawings:

1) *Using aerial thermal imaging and GPR together and detecting from the outside*
2) *Using Pipeline Inspection Gauges (PIGs) to detect leakages from the inside*

So we wrote down the pros and cons and the step-by-step process for them:



Reality Check on our Current Solutions

However, as we progressed, it became apparent that simply combining existing technologies with minor adjustments lacked innovativeness. We also began to scrutinize why many of the solutions outlined in research papers had not been widely adopted in real-world applications. For instance, we discovered that aerial thermal imaging is rarely used in practice due to stringent regulations governing aerial spaces, particularly in areas like Barcelona, where airport traffic complicates the use of flying objects.

This realization dampened our initial enthusiasm and led us to understand that we needed to refine the scope of our problem further in order to come up with our own innovative solutions.

Narrowing Down the Problem

To address these gaps, we recognized the need to deepen our understanding of the underlying issues. For example, what are the root causes of leaks? Is detection really a problem or is fixing it even more difficult? What makes detection so hard? What is the proportion of different pipe materials? Who is involved? etc.

To gather this essential information, we conducted comprehensive online research and interviewed key individuals who could provide expert insights into the complexities of water management (details and findings are elaborated in the next section).

With this new knowledge we created a new (not completely exhaustive) overview that narrowed down the overarching problem of pipe leakages for us to pick a more detailed problem:

Pipes are leaking because the material is compromised through

- *calcium buildup from the water*
- *pressure changes*
- *temperature changes*
- *root of trees and such*

Detecting leaks has issues with

- *predictive detection of leaks*
- *detecting accuracy/distance*

Fixing leaks has issues with

- *time it takes until a detected leak is fixed*
- *complexity of construction work and replacement*

While working collaboratively, we identified a critical issue in our decision-making process: our inability to quickly reach consensus. Our approach typically involved extensive research and fact-gathering before making any decision, which often resulted in a cyclical pattern of contemplating a decision, researching potential issues, and ultimately hesitating to commit due to newfound uncertainties. This tendency to seek further answers through research and interviews frequently stalled our ability to make definitive choices.

To address this challenge, we implemented a structured decision-making strategy. We decided to use a voting system to break the cycle of indecision. This approach helped us to finally converge on a specific problem to focus on: *the time-consuming aspect of fixing pipe leakages*.

Problem Stakeholder

Aigües de Barcelona (Problem Owner): As the principal water provider in Barcelona, Aigües de Barcelona is directly affected by water leakage issues and holds the primary responsibility for addressing and resolving them. Their involvement is crucial, making their role extremely significant in the context of this problem.

Municipalities: Local government bodies play a crucial role as they are impacted by the leakage issues. They require regular updates and must be involved in communication strategies to effectively manage the situation. Agreements or consents from the municipalities are often necessary to proceed with solutions, which places their level of importance at medium.

Citizens and Tourists of Barcelona: While not directly involved in the decision-making or problem-solving processes, both residents and visitors of Barcelona are indirectly affected by water leakages. They experience the consequences of reduced water availability and the disturbances caused by construction and repair work in urban areas. Their stake in the resolution of the problem is considered low compared to the other stakeholders.

Validation Interviews

Technology Interviews

During the third week of the course, we attended interviews with the three ATTRACT technologies. Most of the capacities and possible uses of ULTRARAM and IALL were already quite clear before the interview.

In the case of the H-Cube, we were under the impression that terahertz radiation had much more penetrating potential and that it was already naturally emitted by the sun and/or materials without the need of a source, similar to UV or infrared. Our main idea to use the H-cube to address our challenge was to use the fact that terahertz does not penetrate water to detect underground bodies of water. This could be useful to either find and dig new freshwater wells or to detect water that escaped from pipes to easily detect pipe leakages. Thanks to its small dimensions it would be easy to attach to a flying drone together with the IALL lens to have a compact, fast-focusing terahertz camera to automate detection of underground water.

However, it seems like that would not be possible since we would need a terahertz source behind our target that could only be at most several centimeters thick. There is still a slight possibility that the h-cube could be useful in those kinds of applications:

- The researchers mentioned that the focus of the H-Cube is to work on a wide range of frequencies to have a colored image. However, it would be possible to tune it to detect only very specific frequencies. Working with very specific frequencies, there's the possibility to penetrate much further into the ground and maybe detect water that is not too deep. For this, we would also need a terahertz source powerful enough so that we can image objects through reflection instead of absorption.
- To detect pipe leakages, we also found out about the use of UAV drones with thermal imaging. The idea with those thermal cameras is to look at the temperature of the soil on the surface. Any temperature anomalies in a local region could indicate the presence of water underneath. We wonder if the infrared cameras used for this application are somehow limited in some cases because they are not able to detect radiation of smaller frequencies. What if there's radiation in the terahertz range that can give us much more reliable information? Maybe we've never looked into it because of the lack of light terahertz-cameras. Maybe it makes this method useful in colder climates where the frequencies of thermal radiation are lower.

However, those were very specific uses and required to verify very specific statements for which research was hard to find, so we decided to abandon the idea.

Aigües de Barcelona Report

A week later, we were still determined to find a way to significantly improve the process of detecting leakages and started reading the 2023 report from Aigües de Barcelona. There, we found out that the overall efficiency of the Barcelona water distribution system was already 83,58%, much higher that we anticipated. Turns out that droughts in the past years had already forced Aigües de Barcelona to invest heavily into improving their efficiency.

In the report, they also detailed several of the technologies they were using. We found that many of our ideas were already implemented in some manner:

- From the idea of the **pigs** mentioned in the previous research section, we were looking into possibilities of detecting leaks by inserting a device inside the pipe. The SmartBall they were trying was already doing exactly that.
- One of our ideas was to automatically guess where there could be a potential leak by having many pressure/speed sensors distributed around the network. But using the water meters of each building already gave them quite a wide network of sensors.
- The coaches suggested trying to tackle some of the root causes for leaks, but there was already work done in that area by installing valves to better regulate the changes in pressure inside the pipe.
- To pinpoint the exact location of a leak from the outside, Ground Penetrating Radar was also a solid option, but they already had their own method of doing it using traceable gas.

One one hand, this was bad news because many of our ideas were already implemented. However, this also gave us some information on what was possible or not. On the other hand, since they use the SmartBall and also introduce Helium into working pipes, that means that it is possible to introduce objects into the pipes while running. Additionally, health/safety regulations must allow us to introduce objects and be in direct contact with drinking water as long as the materials exposed to said water are not harmful to humans.

Aigües de Barcelona Interview

Some days later, in the interview we had with Aigües de Barcelona, they insisted that detecting leaks was still a challenging process. After having seen all the work that has been done in that area, we felt like there was very little margin for us to significantly improve their methods or come up with a radically new and much better solution.

Another thing mentioned by the person we interviewed was that even after detecting a leakage, fixing it is not straightforward. Many pipes are below urban ground, which require special permits to set up a construction site and fix. Others may require a special part that is not in stock at the moment and they need to wait for it. All in all, the repair process once a leak was detected could take several days.

At this point, we decided that maybe we could make a much bigger impact if instead of focusing on detecting leaks, we focused on a way to take quick action once detected.

Focused Problem: Time Issue of fixing pipe leakages

The urgency of addressing pipe leakages cannot be overstated. Despite the recognition of this issue, the process of fixing leaks is hindered significantly by time constraints at multiple stages.

Firstly, in the detection and initial response:

Once a leak is detected, the response is not immediate. Municipalities, responsible for the public water infrastructure, must first issue a permit for the construction work required to replace the faulty section of the pipe. This administrative step, while necessary for ensuring safety and coordination with other public services, introduces the first delay in the response time.

Secondly, in the deployment and construction challenges:

After obtaining the necessary permits, the construction company can finally deploy to the site of the leakage. However, reaching the leakage point itself consumes time, especially in densely populated urban areas where navigation can be complex and disruptive. The actual construction work involving the excavation of the affected area is a time-consuming and labor-intensive process. Urban environments pose additional challenges due to the dense network of existing infrastructure, such as electrical lines, communication cables, and other utility pipes, all of which must be navigated carefully to avoid further damage.

Thirdly, in material availability and logistics:

A critical factor in the timeline for fixing leaks is the availability of suitable replacement pipes. The specific material and size of the pipe needed may not be readily available locally, necessitating transportation from other locations. This logistics issue not only extends the repair time but also increases the cost and complexity of the operation.

During all these stages - from detection and permitting to excavation - water continues to leak from the damaged pipe.

This not only results in significant, continued water loss, but also increases the risk of damage to the surrounding infrastructure and environment. The longer the water leaks, the greater the potential for erosion, road damage, and further disruption to the community.

We think there has to be a better way.

Solution Ideation

Addressing the time-consuming nature of fixing pipe leakages necessitates innovative thinking and the exploration of various solutions. We considered the following ideas to reduce the time needed to fix leaks:

1. Local Availability of Repair Materials

Improving the local stock of diverse pipe materials and sizes could reduce the delays caused by sourcing and transporting these essential components. However, this solution primarily addresses logistical challenges and lacks a novel, transformative element. We were not too excited by this idea

2. Streamlining Administrative Processes

Accelerating the administrative procedures, such as the issuance of permits, is undoubtedly beneficial. Reducing bureaucratic delays could speed up the commencement of repair works. Yet, this approach does not directly tackle the technical aspects of the repair process itself and is more about improving existing frameworks rather than introducing a new solution. We did not think this idea had a lot of potential either and was lacking technological innovative aspects.

3. Enhancing Construction Efficiency

Optimizing construction techniques to work faster might seem straightforward but is limited in potential impact. Urban environments inherently complicate construction activities, and significant improvements in speed without compromising safety or quality are challenging to achieve. Thus, we quickly deemed this solution less feasible for substantial innovation and impact.

4. Robotic Leak Management - The Promising One

The most promising and innovative solution emerged when we considered an intermediate approach to manage leaks until permanent repairs could be made. The concept involves deploying a robot into the water pipes that can temporarily seal leaks. This idea was inspired by the use of robots inside the pipes by Aigües de Barcelona in a pilot project to detect leakages. The potential for inserting a different robot not for detection but for immediate interim stopping of water loss sparked significant interest and excitement among us.

One thing we learnt before is to not be too logical about everything, so once we were all hyped about the idea, we started to define the functions of the robot and started designing it, dealing with all the challenges one by one.

So our final idea was to create a robot capable of navigating through the pipe system, identifying leaks, and applying a temporary seal. We agreed to further pursue this idea and went into the design process. In this paper the design of our process is elaborated on in a later chapter.

Designing the Robot

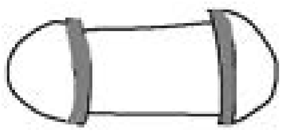
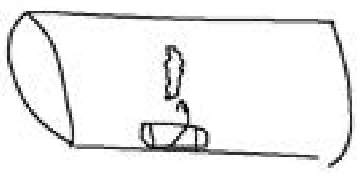
Once we finally decided on making a robot to temporarily seal the leaks, we've identified two main challenges that our design would need to address to be a viable solution: navigating through a highly pressurized water pipe and sealing the leakage ensuring it won't get removed with the flowing water.

Navigating Inside the Pipe

It's not trivial to move inside the pipe while resisting the strong currents of water inside of the pipe. The following are examples of the explored options to ensure the robot is able to properly navigate the pressurized water pipe:

Magnetic adhesion

Magnetic adhesion involves equipping the robot with strong magnets that allow it to cling to the metal walls of the pipe. This method provides a stable and reliable way for the robot to maintain its position and orientation within the pipe, even against the force of the water pressure. The magnets can be electromagnets, allowing the robot to control its attachment and detachment from the pipe walls as needed. This method is particularly effective in metal pipes and offers the advantage of not being affected by the high water pressure. Regardless of being a reliable option, magnetic adhesion is ineffective in non-metallic pipes, such as those made of PVC, concrete, or other composite materials. Additionally, some metal pipes are lined with non-magnetic materials (such as plastic or epoxy coatings) to prevent corrosion or reduce friction. These linings can also inhibit the effectiveness of magnetic adhesion.

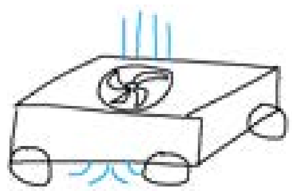
Suction mechanisms

Suction wheels or cups use vacuum pressure to adhere to the pipe walls. The robot would have wheels or cups with suction mechanisms that create a vacuum seal against the pipe surface. This technique is highly effective for smooth surfaces and provides strong adhesion, enabling the robot to move steadily despite the water pressure. The suction cups can be activated and deactivated as the robot moves, allowing for continuous and controlled movement. This method is versatile and can be adapted to various pipe materials and conditions.

Hydrodynamic Downforce Design

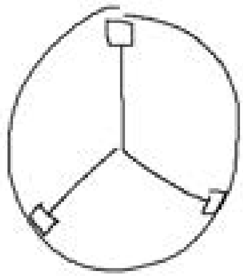
This method utilizes the principles of fluid dynamics to create a natural downforce. By designing the robot's shape and components to harness the water flow within the pipe, the robot is naturally pushed against the pipe walls as it moves.

Motorized downforce



This method leverages the principles used in automated pool cleaners, which use motorized downforce to press the cleaner against the pool surface. In the context of a highly pressurized water pipe, the robot would use motors to generate a downward force that pushes it against the pipe walls. This force counteracts the water pressure, allowing the robot to maintain contact with the pipe surface. The motorized downforce system can be adjusted based on the pipe's pressure conditions, providing a flexible and adaptive solution.

Triangular disposition



A robot with three wheels arranged in a triangular configuration can press each wheel against the pipe wall. This design ensures that the robot is evenly balanced and stable within the pipe. Each wheel can be spring-loaded or motorized to maintain constant pressure against the pipe walls, ensuring that the robot remains in place and can move efficiently. This setup provides robust contact with the pipe surface, distributing the force evenly and allowing for smooth navigation even under high pressure. This design may result mechanically simpler than some other methods, nonetheless, the wheels need to provide sufficient direction to grip the pipe walls, which may vary in different materials, and continuous pressure against the pipe walls could lead to faster wear on the wheels, requiring more frequent maintenance.

A Seal that Seals

The following are the sealing options explored to guarantee proper sealing and ensure that the seal won't get removed by the by the water currents:

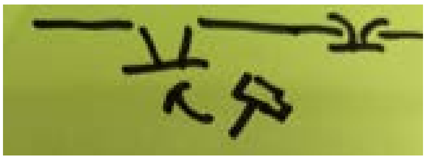
Triangular "Thumbtack" Plug

The triangular "thumbtack" plug involves inserting a triangular-shaped plug into the leak. The plug's shape allows it to wedge securely into the hole, with the wider base on the outside and the narrow end pushed through the leak. The design allows for straightforward insertion into the leak by the robot, however, the plug needs to be appropriately sized for the leak, requiring a range of plug sizes to be carried by the robot.

Screwable Plug

A screwable plug is designed to be inserted into the leak and then twisted to create a tight seal. The threads on the plug grip the edges of the hole, ensuring a secure fit. This design may require diversity in screw sizes to be carried by the robot. This option also requires precise alignment and sufficient torque to screw in the plug, which might be challenging for the robot in a confined space.

Moldable / Flexible Foldable Pieces

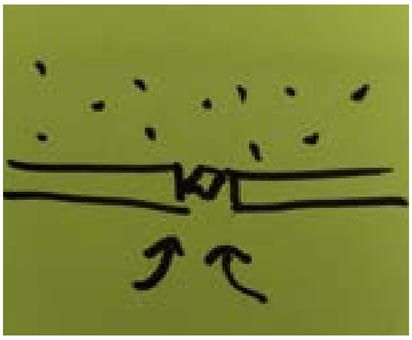


Moldable pieces are inserted into the leak and then expanded or molded to fit the internal shape of the pipe. These pieces conform to the pipe's contours, providing a custom fit around the leak. This design ensures a tight seal by conforming to the specific shape and size of the leak and can be adapted to a variety of leak shapes and sizes. Nonetheless, the material must be robust enough to withstand high pressure and not degrade over time and the robot must be able to control the expansion or molding process to ensure a secure seal.

Taping

This method involves the robot applying a strong, adhesive tape over the leak from inside the pipe. The tape needs to be highly adhesive and durable to withstand the water pressure. This option may result simple to apply, with the robot placing the tape over the leak and can be used on various leak sizes and shapes. Nonetheless, the tape's adhesive must be strong enough to stick under high pressure and potentially wet conditions.

Blocking Material



This method involves inserting a blocking material directly into the crack or leak. The material is designed to expand or set in place, creating a tight seal that is held in position by the internal water pressure and an external barrier that prevents the material from being pushed out.

Liquid Gel or Resin

This method involves injecting a liquid gel or resin into the leak. The substance is designed to harden upon contact with water or after a certain period, creating a solid, durable seal that adheres to the pipe walls. The gel or resin must be formulated to be non-toxic and safe for use in potable water systems, ensuring no contamination. This solution may allow the creation of a strong, permanent bond with the pipe material once hardened and can be injected directly into the leak, making it relatively easy for the robot to apply. On the other hand, the gel or resin must be compatible with the pipe material and the water chemistry to ensure proper adhesion and durability. In the same manner, the robot needs to ensure that the material stays in place while it cures, which can be challenging in high-flow conditions.

Each sealing method offers unique advantages and challenges. The triangular "thumbtack" plug provides a simple and secure fit but may be size-specific. The screwable plug offers a strong seal but requires precise installation. Moldable/flexible pieces provide a custom fit but need durable materials and precise expansion control. Taping from within is easy to apply but relies on strong adhesion. Patches can be highly adaptable but need to be securely fastened. The liquid gel or resin offers a contamination-free, strong bond but requires curing time and material compatibility. The choice of method depended on the specific conditions of the pipe and the nature of the leaks encountered.

Final Design

Design

After thorough evaluation of various options for both navigation and leak sealing within highly pressurized water pipes, we arrived at a solution that best meets the specific challenges and requirements of this environment. Our chosen solution utilizes a plug for sealing leaks and a combination of a motorized downforce system with a stabilizing arm for navigation. We selected the plug method for sealing leaks because it provides a straightforward and robust solution that is easy to deploy. The plug can be quickly inserted into the leak and secured, offering an immediate and effective seal. This method reduces the need for complex mechanisms and precise alignment, making it more practical for use in high-pressure environments. For navigation, we evaluated magnetic adhesion, suction wheels/cups, hydrodynamic downforce design, and three wheels in a triangular disposition. Magnetic adhesion, although stable on metal pipes, is ineffective on non-metallic pipes and susceptible to interference from external magnetic fields. Suction wheels or cups offer strong adhesion on smooth surfaces but require vacuum maintenance and can struggle under high pressure. The hydrodynamic downforce design is energy-efficient but requires precise engineering and may vary in effectiveness with changes in water flow. The triangular wheel configuration provides balance and stability but may not adapt well to variable pipe conditions and can lead to faster wear.

Our chosen navigation solution uses a motorized support arm that stretches from the robot to the opposite pipe wall. This approach provides several key advantages: the stabilizing arm ensures the robot remains securely in place, even under high water pressure and turbulent flow conditions. Additionally, this method offers precise control over the robot's movement and position, which is crucial for navigating complex pipe networks and ensuring the successful deployment of the sealing mechanism.

Our chosen solution of using a plug for sealing and a stabilizing arm for navigation effectively addresses the challenges of operating within highly pressurized water pipes. This approach combines simplicity, reliability, and adaptability, ensuring that the robot can navigate efficiently and seal leaks securely, regardless of the pipe material or internal conditions. By evaluating and rejecting alternative methods, we determined that this solution best meets the specific needs of our application.

Adding to those two main ideas:

- We've decided to use acoustic sensors to orient and navigate inside the pipe. Acoustic sensors have been widely used to detect leaks and it's exactly how the SmartBall works. Since our robot's main sensory input was sound, neither H-cube nor IALL were a good fit for our solution. The disposition of the sensors can be seen on the sides of the lower cylinder of the robot, with three sensors (only two are visible in the previous figure) it should be possible to triangulate the origin of sounds and locate leaks.
- We've decided to use ULTRARAM and dedicated AI hardware to process all the information coming from the sensors and control the motors to move the robot accordingly. Thanks to ultraram and the dedicated AI hardware we can ensure that both memory and computing are very energy efficient. Those components will be located in a sealed compartment inside the upper cylinder, as seen in the following figures.

- Finally, by using a heavier material for the lower cylinder together with the air chamber on the upper one, we expect the robot to orient vertically so the support arm can attach correctly to the top of the pipe. Also, in order for the wheels to be parallel to the direction of the pipe, we’ve added some hydrodynamic fins to the back of the robot so that it will point in the direction of the water flow, similar to how windmills have tails that always make them point in the direction of the wind.

Impact

We are still waiting for concrete impact related data from Agües de Barcelona. Among other questions, we asked for the average number of leaks, more accurate data on how long it takes on average to detect a leak, and how much water is lost. Since we are missing this data, we are estimating the impact.

We estimate that each leak that we seal early could save lots of water. If we take a look at a couple publicly reported leaks in the Barcelona metropolitan area, one in Santa Coloma de Gramenet was losing 86.000 liters/day, while one in Badalona was losing 180.000 liters/day. Of course, the amount of water lost can vary a lot depending on the pipe's pressure and diameter; however, given the numbers for the previous two examples, we will estimate an average leak to lose about 100.000 liters/day. These two leaks in particular had been leaking for over a year, which is more likely due to negligence instead of justifiable delays, so it would be a bit unfair to use these figures to quantify our impact. Since we don't have the average time it takes for a leak to get fixed in the Barcelona metropolitan area, we are going to use the numbers provided from Thames water. In their web page where they mention that thanks to an improvement of their procedures, they could get the average time to address a leak down to 5 days. Therefore, if the average leak loses about 100.000 liters/day and takes an average of 5 days to get fixed, each leak on average is responsible for **half a million liters** of wasted water that could be prevented with our solution. We estimate that the deployment of our solution will take an average of 2h (most of if used on physically going to the nearest access point to introduce the robot). We don't have information on how many leaks of such magnitude occur on a yearly basis in the AMB, so we can't have an estimate on the global impact but even with very few occurrences of those leaks we will already be saving amounts of water in the millions of liters.

We've been focusing on Barcelona for now, but our proposal could be used in pipes all over the world. It is hard to get information for a global study, but there are certainly many places with more frequent leaks and longer response times than barcelona. In conclusion, the impact this could achieve if deployed on a global scale would be truly transformative.

Considerations

Compared to other existing robots, our solution can withstand the strong water currents inside the pipe, and has enough strength to keep the leak sealed for many days and we think that it has the potential to make a big positive impact in the field of maintaining water distribution networks.

Despite this, we've also identified some potential situations where it could also have unintended negative effects:

- **Contamination of the water:** This robot is intended to work inside pipes that transport drinkable water. Therefore, it is important to make sure that our robot does not leak any substances that can be harmful to humans into the water. From the parts that our robot is composed of, the only parts that could release any kind of undesired substance are the battery or electronics. Those parts should already be in a sealed environment not only to protect the water from them but also to protect them from the water. Accidents can happen, but unless a robot is left inside the pipes for very long periods of time (years) we are quite confident that this should not be a problem.
- **Removing the incentives to maintain and fix the pipes:** By giving a much faster and cheaper solution to leaks compared to a conventional repair, we are also concerned that organizations managing water distribution networks may be disincentivized to conduct the proper repairs afterwards. While our invention prevents the water from leaking, it does not recover the pipe's original structural integrity. Meaning that if the leak is left unattended for a long period of time, the pipe could suffer more serious damages like a complete rupture, which could mean a much higher water loss than we originally prevented. Apart from losing more water, this scenario would also mean losing more money. To some extent then, we trust organizations will try to make adequate use of this technology since it is also in their best interest to do so. But there is a possibility that it could be abused.

- **Failsafe:** We also considered the problem of the robot not being able to detect a leak or seal it accurately. In this case, the robot will still be kept in place without issue and simply stop moving. Since the robot does not have any negative impact, it can still be picked up, the data can be analyzed, changes can be made, and it can be employed again.
- **Interaction with other nanobots:** This is a bit more tricky. But in our opinion the design can be iterated so that the overall area that nanorobots could hit is reduced. Additionally, without our solution, there is the possibility of nanobots passing through the leak, and this risk at least is minimized with our solution. Nevertheless, communication with stakeholders to find out more about the deployment areas of other nanobots could prove helpful to avoid unwanted negative effects.

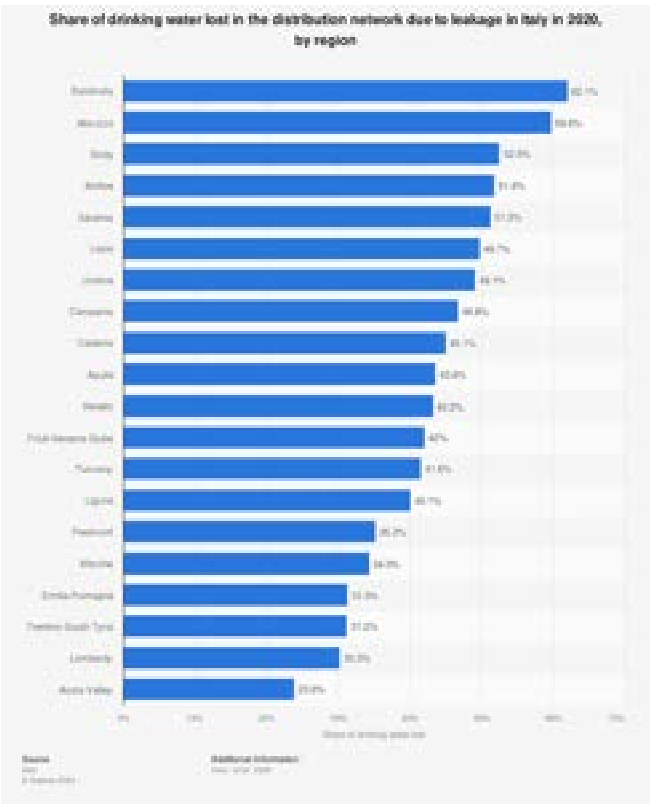
Prototype iteration and improvements

We do believe that our solution can be tested, but we think that first active tests under high water pressure of our design might prove to not be without challenges. We want to highlight the importance of continuous improvement and ideation of the design with an open mindset, especially in the beginning to improve the functionality of the robot. Further information about detailed processes and other data from Agües de Barcelona should be considered closely.

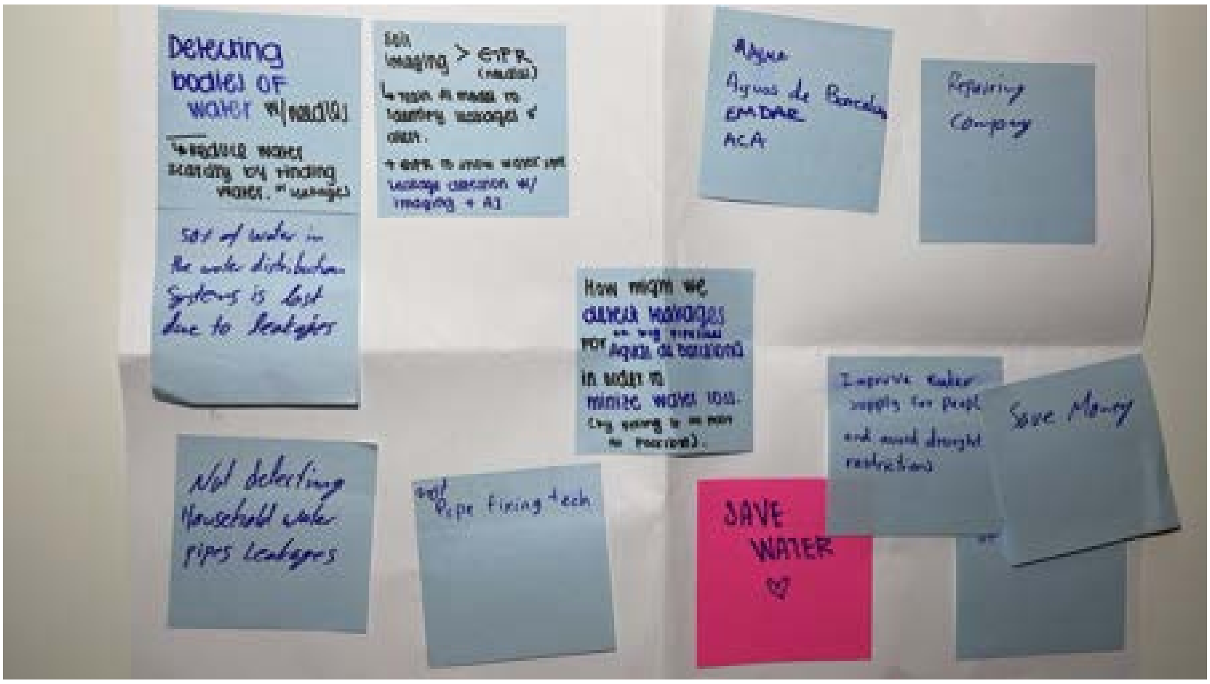
Appendix

1. Our Business Model Canvas:

2. Supporting statistic for pipe leakage problem:

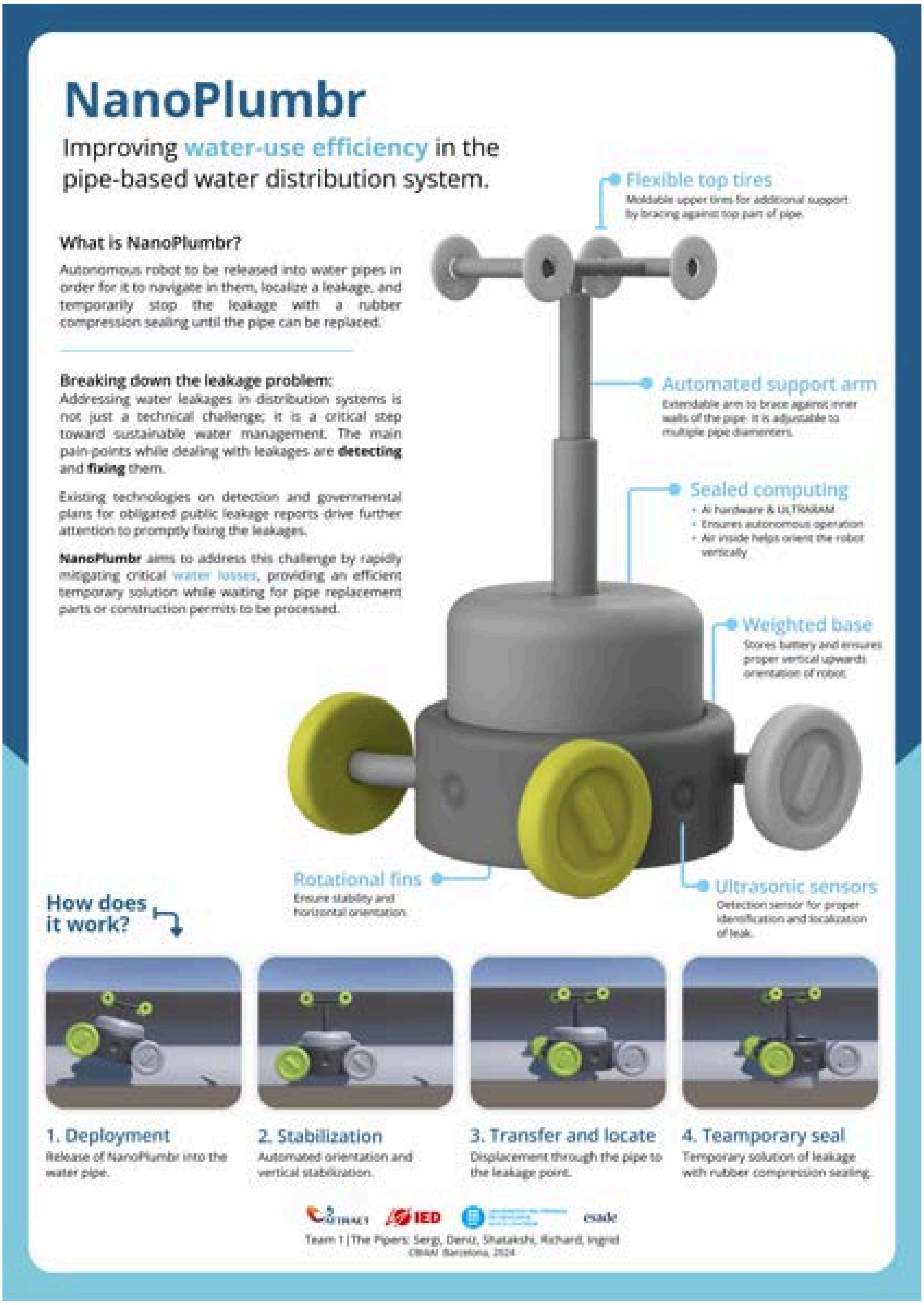


3. First Ideation HMW statement:



4. Logo of nanoPlumbr:

5. Poster of our Project:



6. Link to our Demo Video

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