Final Year Project Report

Hybrid mobile in-pipe robot for inspection and maintenance

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A thesis submitted in part fulfilment of the degree of

BSc in Robotics and Mechatronics

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May 8, 2025

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Abstract

In the contemporary world, pipelines serve a vital function in the transportation of essential resources, including water, oil, and gas. As a consequence of the ongoing process of urbanization, the number of pipelines is increasing dramatically on an annual basis. The timely maintenance and inspection of pipeline infrastructure is becoming increasingly challenging due to the length of the pipelines and the limited accessibility from the outside. Consequently, specific sections of the pipeline must be repaired from the interior. This research project proposes a novel hybrid in-pipe robot equipped with a manipulator for maintenance purposes. This hybrid robot can inspect and perform refurbishment tasks inside the pipeline, such as removing debris and conducting welding operations. In addition to its physical capabilities, the system integrates an augmented reality interface to enhance inspection and interaction. By projecting live sensor data and 3D scanned maps into a mixed reality environment, the system enables immersive spatial awareness, intuitive control without reliance on traditional interfaces, and real-time anomaly detection assistance for the operator. To prove the concept, a laboratory prototype was constructed for experimental purposes in a controlled environment. This research paper is organized as follows: robot design concept, robot control, augmented reality visualization, anomaly detection and inspection, and in-pipe maintenance.

Acknowledgments

We would like to express our deepest gratitude to our supervisor, Dr. Azamat Yeshmukhamertov, whose invaluable mentorship guided us through every stage of this project. His unwavering support, insightful feedback, and hands-on assistance with navigation, equipment, and regular meetings were instrumental in the successful completion of our work.

We are sincerely thankful to Manat Nursultan, a second-year Master's student in Biomedical Engineering and member of the ARMS Laboratory, for his practical contributions to the project. His expertise in electronic wiring, soldering, and robot assembly, along with his assistance in experimental data collection and video documentation, greatly enhanced the technical execution of the system.

We also wish to acknowledge Dr. Tolegen Akhmetov, PhD in Robotics and specialist in augmented reality systems, for his generous guidance in learning and working with AR headsets, particularly the HoloLens 2. His support in navigating the Unity environment was invaluable in developing the visualization component of the system.

Special thanks go to our families, Jigi 25, SanMarinad, and Okuma for their constant encouragement and mental support throughout this journey. Their belief in us provided strength during challenging times.

We would also like to thank our course instructor, Professor Anara Sandygulova, for her valuable guidance, dedication, and support throughout the course.

Finally, we extend our appreciation to everyone who provided encouragement, advice, and resources throughout this research endeavor.

Chapter 1: **Introduction**

Pipelines serve as the lifelines of modern society, silently transporting essential resources like water, oil, and gas over long distances to sustain urban centers and industries. Ensuring their reliability and structural integrity is crucial, as any malfunction can lead to serious environmental damage or economic disruption. This makes routine inspection and maintenance essential. Traditional inspection practices often depend on human labor, which can be risky and inefficient. However, the emergence of robotic technologies has revolutionized how these vast pipeline systems are monitored and maintained.

When pipelines are above ground, out-pipe inspection can be carried out by ground or aerial robots, offering safer and more accessible viewpoints for engineers. In contrast, in-pipe robots operate from within the pipeline, handling tasks such as checking for corrosion, clearing blockages, and performing maintenance. Some of these, known as PIGs (Pipeline Inspection Gauges), move through the pipeline by harnessing internal pressure, though they usually can't transmit real-time data.

Robotic systems are generally categorized by their movement and steering mechanisms. Wheeled robots are popular for their speed, low energy consumption, and simple design, sometimes incorporating screw drives to improve grip and balance. Crawler robots, which use treads similar to those on tanks, provide strong traction and can adapt to different pipe sizes, though they tend to be more complex and energy-intensive. Free-floating robots use the pipeline's fluid flow for propulsion, making them ideal for inspecting lengthy stretches. Worm-like robots, made from flexible materials, excel in navigating narrow or winding pipes but are typically slower and more complex in design. PIG robots, while durable and commonly used in industry, cannot perform real-time maintenance tasks.

A range of inspection technologies is employed in these systems, including magnetic flux leakage, ultrasonic sensors, and stereo vision cameras. These tools help identify signs of wear such as corrosion, cracks, or blockages that could compromise the pipeline's function over time.

Even though robotic systems and sensors have improved pipeline inspections, it's still difficult for engineers to fully understand the inspection data just by looking at normal screens or reports. It's hard to picture exactly where problems like cracks or corrosion are inside the pipeline. That's why in this project, we wanted to make it easier for engineers to "see" the inside of the pipeline in a more natural way. We decided to use the MetaQuest headset, a popular virtual reality device known for its immersive 3D visualization capabilities, to let them view inspection data in 3D, so they can explore it as if they're inside the pipeline themselves. Virtual reality headsets like the MetaQuest have been increasingly used in fields like education, training, and design, and here we apply it to pipeline inspection. This way, they can better find issues and decide what repairs are needed. Our project brings together two parts: one focused on the maintenance side, and the other focused on connecting the Meta Quest for immersive inspection visualization. Together, we're trying to create a more effective and user-friendly system for pipeline inspection and maintenance.

Chapter 2: **Background Research**

Some designs, known as pigging robots or PIGs, exploit the pipeline's own pressure for propulsion, although they typically cannot relay real-time data [1]. Across these approaches, robots are often classified by their locomotion and steering mechanisms [2]. For example, wheeled robots are favored for their speed, energy efficiency, and relative simplicity, sometimes employing a screw drive for traction and stability [3, 4, 5, 6]. Crawler robots, which use track-like wheels, offer strong traction and adaptability to certain pipe diameters, although their higher energy draw and mechanical complexity can be disadvantages [7, 8]. Free-floating robots rely on the flow of the fluid itself for propulsion, making them highly effective for extremely long pipelines [9]. Meanwhile, worm-type robots leverage soft, flexible structures to navigate tight or winding spaces, though they often sacrifice speed and design simplicity [10, 11]. PIG-type robots represent another specialized class: although they are robust and widely used in industry, they lack the capacity for on-the-spot maintenance [12]. Inspection technologies vary considerably, spanning magnetic flux leakage [13] to ultrasonic methods and stereo camera systems. These help detect corrosion, cracks, or debris that could weaken pipes over time.

Chapter 3: **Methodology**

3.1 Detailed Design and Control

The wall-pressed in-pipe robot was specifically designed for the inspection and maintenance of pipelines with diameters ranging from 350 to 400 mm (Fig. 3.1). The robot features three actuators arranged symmetrically at 120-degree intervals, forming an equilateral triangle. This configuration ensures balanced distribution of force and torque across the system. All actuators are connected to a central module that houses the essential electronic components.

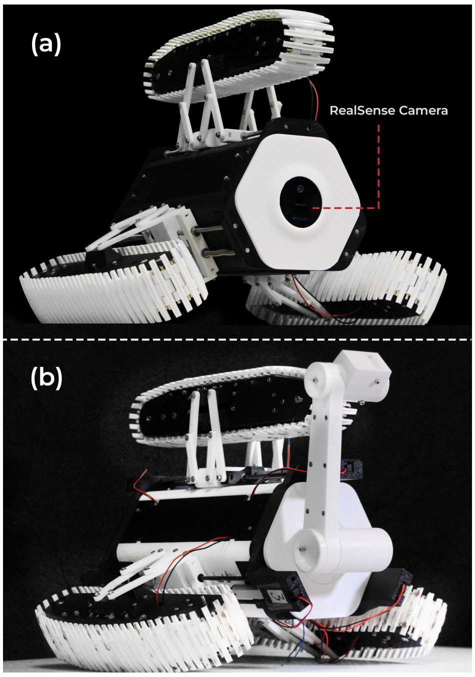


Figure 3.1: a) Inspection module view b) Maintenance module view

The robot's front section is equipped to handle both inspection and maintenance tasks. For maintenance operations, an endoscopic camera is mounted on the manipulator's tool section. For inspection purposes, a RealSense camera is integrated, as illustrated in Fig. 3.1. This modular camera setup allows the robot to be adapted for different operational needs.

3.2 Design for maintenance

The in-pipe robot is equipped with a manipulator with four degrees of freedom (DOF) connected to its head. This allows the robot to be more versatile and functional in conditions of limited space in pipes. The manipulator constitutes an indispensable component of the robot's operational capabilities, offering precise control and adaptability to a vast array of tasks. At the distal end of the manipulator is an end-effector that is equipped with an endoscopic camera. The camera displays the internal space of the pipe via real-time wireless communication, enabling the manipulator to receive precise feedback and control its movements.

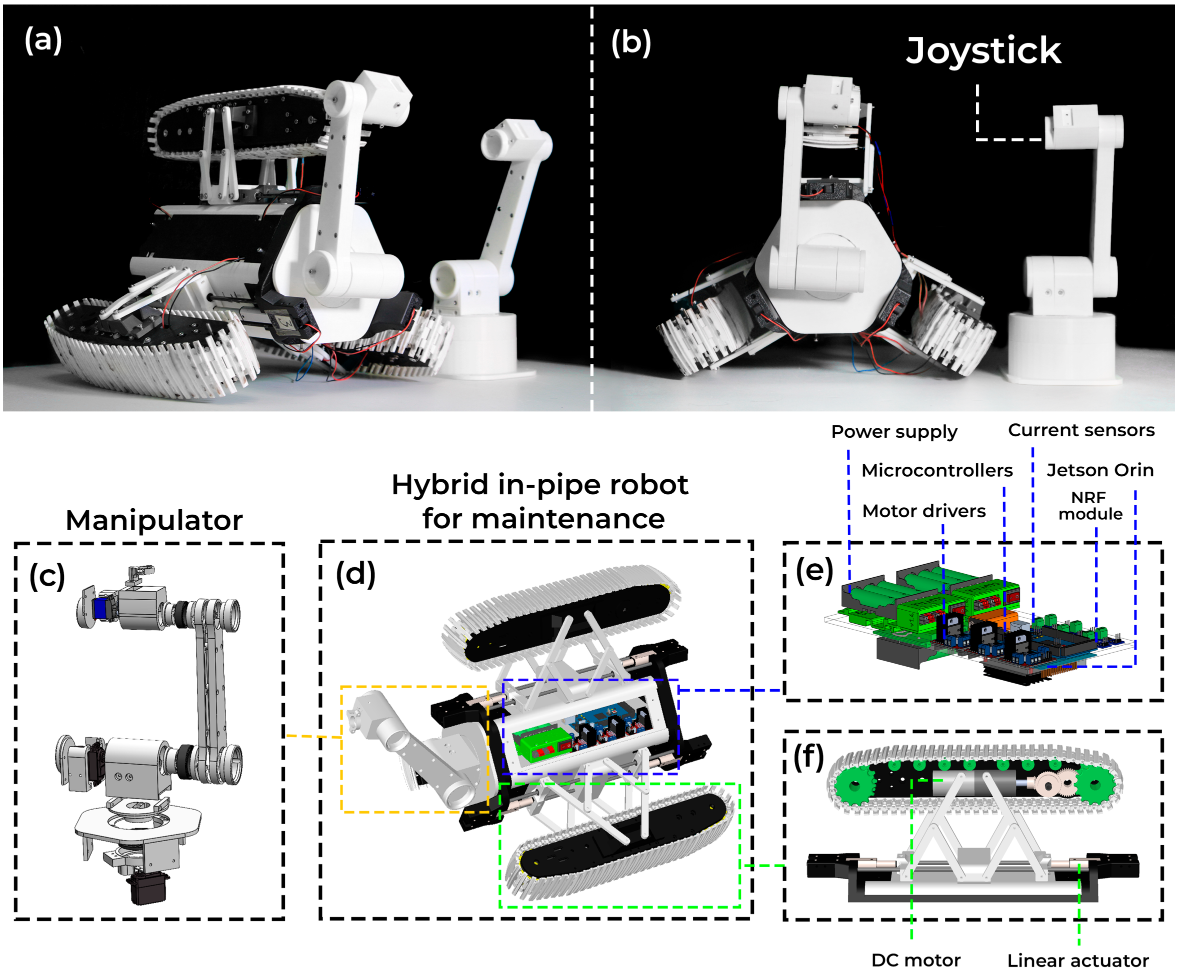


Figure 3.2: General CAD design. a) Manipulator part for pipe maintenance work. b) General assembling of the robot for maintenance. c) Robot electronic board d) Robot active expansion mechanism and actuator

3.3 Central block design

The in-pipe robot features a four-degree-of-freedom (DOF) manipulator mounted on its head, enhancing its versatility and functionality in the confined environment of pipelines. This manipulator plays a crucial role in the robot's operation, providing precise control and adaptability for a wide range of tasks. At its distal end, the manipulator is equipped with an end-effector that houses an endoscopic camera. The camera wirelessly transmits real-time visuals of the pipe's interior, enabling accurate feedback and precise control of the manipulator's movements.

3.4 Actuation system design

The proposed actuation system is designed with the motor housed internally within the robot's chassis, enhancing the overall protection level of the in-pipe robot. This internal placement shields the motor from external environmental factors and mechanical damage. Additionally, the chassis includes space for a gearbox, which allows for the adjustment of motor speed and torque to meet operational demands.

The robot's track is specifically tailored to the pipe environment it operates in. Unlike standard off-the-shelf tracks, this custom design incorporates a curved surface (Fig. 3.2) to optimize both traction and performance. This modification significantly improves the robot's ability to navigate through pipelines by ensuring better grip on the inner walls and facilitating smoother, more efficient movement.

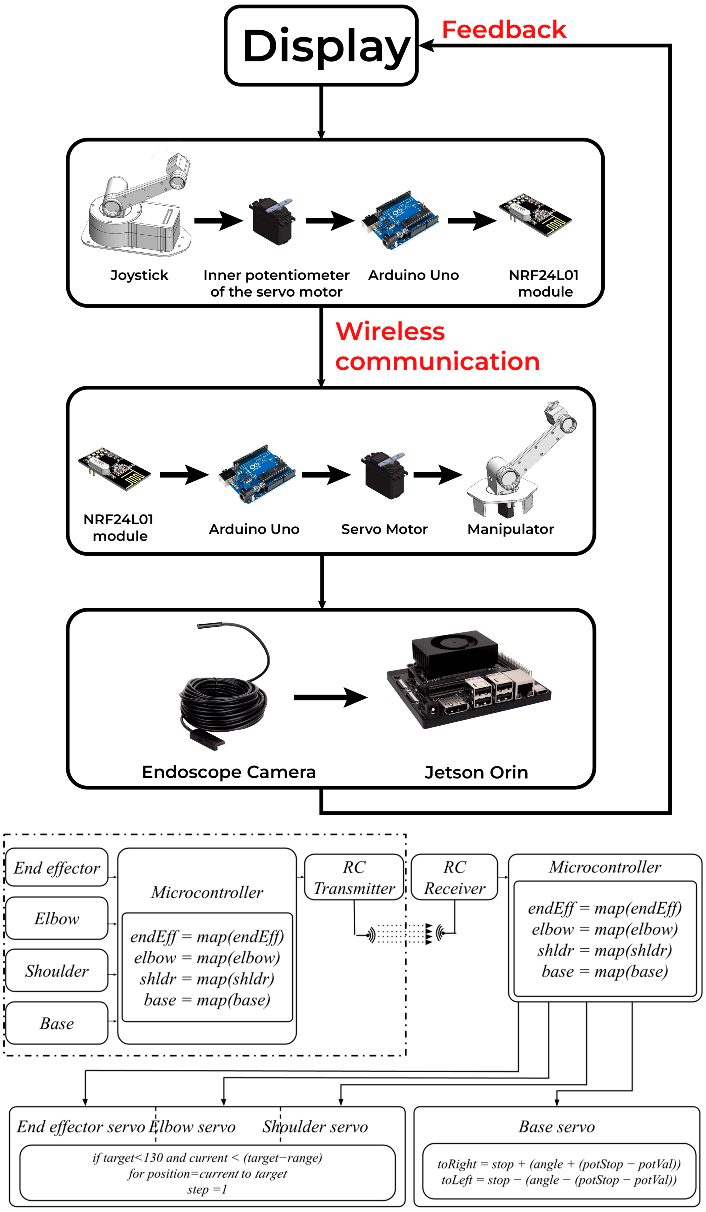


Figure 3.3: Tele-operating control with master and slave method

3.5 Manipulator Control

The manipulator control system is based on the master-slave methodology. In order to facilitate the efficient operation of the manipulator within the pipe, a joystick has been developed which incorporates the same degree of freedom (DOF) mechanism as the manipulator itself. This enables the manipulation of the manipulator for the purpose of task performance in real time. Initially, the potentiometer values from the joystick joints are obtained and transmitted to NRF24L01 module (Fig. 5.8). The data are then conveyed to the receiver module via wireless communication. Subsequently, the data are converted to the requisite values and employed for the control of the manipulator's joints and motors. Furthermore, an endoscope camera is employed for the observation of the internal space of the pipe. The system transmits feedback to the display, which allows the user to observe the process and simultaneously control the manipulator in real time.

3.6 Main agent: AR inspection

The main inspection agent used in this project is a robotic platform equipped with sensors and designed for autonomous movement inside pipelines. This robot is responsible for capturing inspection data, such as images or sensor readings, which are later processed and visualized using augmented reality (AR) tools.

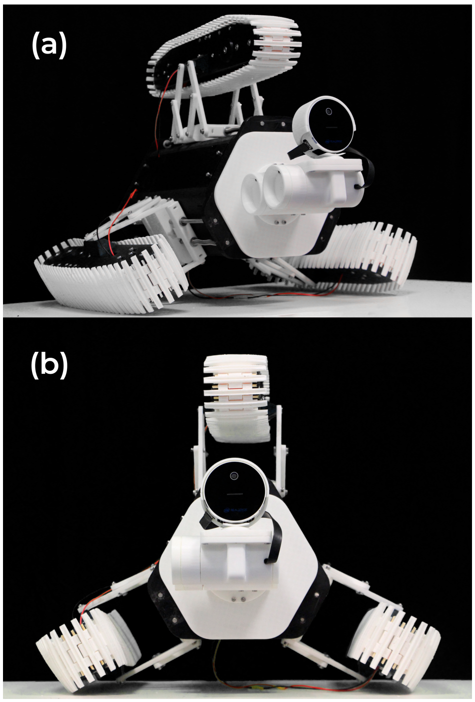


Figure 3.4: a) AR inspection agent b) Front view

Figure 3.4 shows the inspection robot from two different angles: (a) a side view and (b) a front view. The robot features adaptable legs for stability inside the pipeline and a front-mounted camera for data collection. This robot acts as the primary data source for the AR inspection system, enabling engineers to visualize pipeline conditions in an immersive environment.

A key component of the inspection system is the RealSense camera, as highlighted in Figure 3.5(b). The camera is mounted on the front of the robot and is responsible for capturing

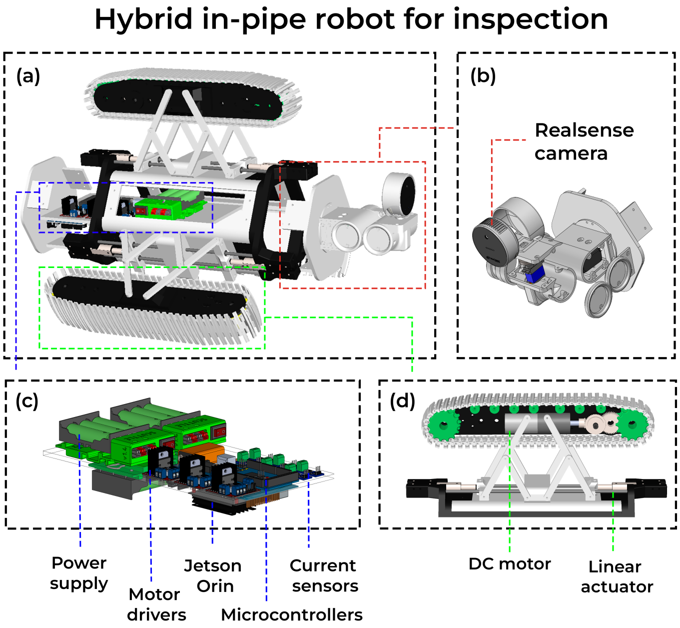


Figure 3.5: a) Modeling of hybrid in-pipe robot b) 2DOF Manipulator c) Module of electronic devices d) Locomotion module

high-resolution visual and depth data inside the pipeline. This sensor plays a crucial role in enabling detailed inspection by providing both color images and 3D point cloud information. The data collected by the RealSense camera serves as the primary input for the augmented reality (AR) visualization, allowing engineers to view the pipeline interior in an immersive environment. The camera's placement and angle are optimized to ensure maximum coverage of the pipeline walls as the robot moves forward.

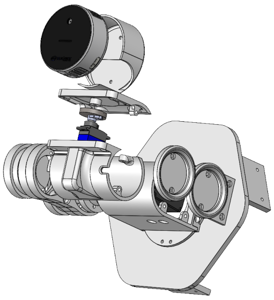


Figure 3.6: Umnitsa

Figure 3.6 shows the Umnitsa module, which functions as a pan and tilt mechanism to control the orientation of the RealSense L515 camera during the inspection process. The module uses an MG92B servo for tilt control and an HS-485HB servo for pan control, allowing horizontal and vertical adjustments of the camera. This design enables the system to capture images from multiple angles inside the pipeline without repositioning the entire robot. The RealSense L515 camera collects depth, RGB, and infrared (IR) data streams, which are merged to create a view of the pipeline's interior. Additionally, the system streams an anomaly detection frame in real time, supporting the identification of potential defects or irregularities during inspection.

3.7 Master and Slave control

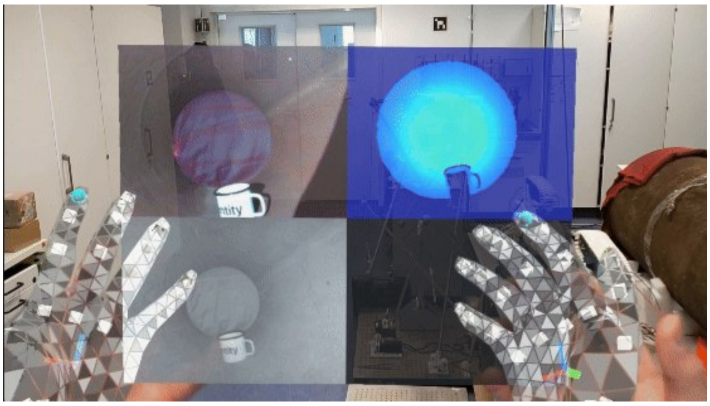


Figure 3.7: Combined frames

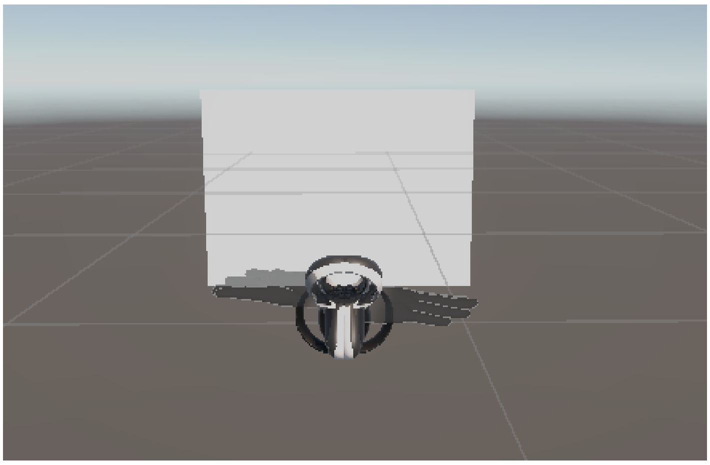


Figure 3.8: Unity and applying Dynamic texture to Quad

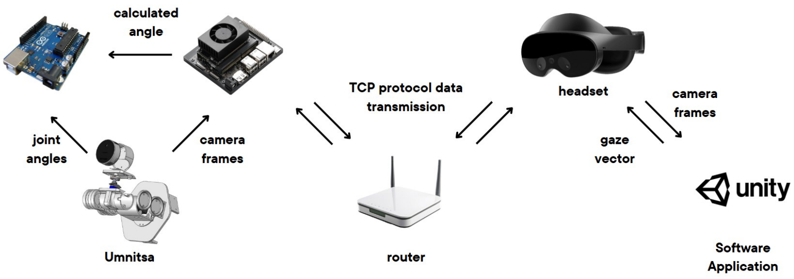
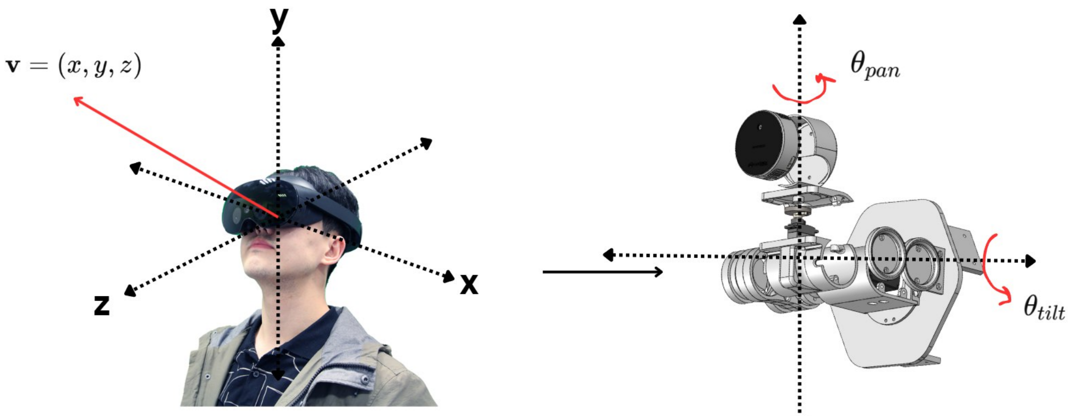


Figure 3.9: Control diagram

Figure 3.7 illustrates the combined visualization of the inspection data streams inside the augmented reality environment. In this setup, depth, RGB, and infrared frames are displayed simultaneously on a virtual panel, allowing the user to view and compare different data types in real time through the MetaQuest headset. This interface enables inspectors to interact with the inspection data more intuitively during analysis. Figure 3.8 shows the implementation of the dynamic texture mapping in Unity, where the combined video stream is applied to a virtual Quad object. This approach allows the live inspection feed to be projected onto 3D objects inside the Unity scene, providing a more immersive and interactive visualization experience for the user.



$$\theta_{tilt} = \arctan\left(\frac{y}{\sqrt{x^2+z^2}}\right) \times \frac{180}{\pi} \quad \theta_{pan} = \arctan\left(\frac{z}{x}\right) \times \frac{180}{\pi}$$

$$0^\circ \leq \theta_{pan} \leq 180^\circ \quad \text{and} \quad -90^\circ \leq \theta_{tilt} \leq 90^\circ$$

Figure 3.10: Calculating the motor angles

Figure 3.9 presents the control diagram of the AR inspection system, illustrating the interaction between the hardware and software components. The Umnitsa module captures visual data from inside the pipeline and transmits the camera frames to the Jetson Orin for processing. The Jetson Orin calculates the necessary joint angles for the pan-tilt mechanism based on the gaze direction provided by the MetaQuest headset. These calculated angles are then sent to the Arduino controller, which adjusts the servos of the Umnitsa module to align the camera. Meanwhile, the camera frames are streamed via TCP protocol over a local network router to the MetaQuest headset, where they are visualized in real time within the Unity application. The gaze vector from the headset is also transmitted back through the system to guide camera orientation, creating a closed-loop interaction between the user's view and the camera's position inside the pipeline.

Figure 3.10 illustrates the process of calculating the motor angles required to align the Umnitsa camera with the user's gaze direction. The gaze vector v=(x,y,z) is captured from the MetaQuest headset, representing the direction in which the user is looking within the 3D space. Using this vector, the pan and tilt angles are computed through trigonometric functions, as shown in the equations. These angles determine how the camera should rotate horizontally and vertically to match the user's line of sight. Once calculated, the angles are sent to the motor controllers to physically orient the camera, allowing the system to follow the user's gaze in real time and improve inspection interactivity.

3.8 Mixed Reality Setup

Figure 3.11 illustrates the system workflow for detecting and visualizing objects inside the pipeline using a combination of robotic inspection and mixed reality interaction. The process begins with the inspection robot detecting an object inside the pipe, such as a defect or foreign object. The robot uses RTAB-Map for simultaneous localization and mapping (SLAM) to generate a 3D point cloud of the pipeline interior. This scan data is then processed to create a mesh representation in PLY format. The mesh is subsequently converted to an OBJ file

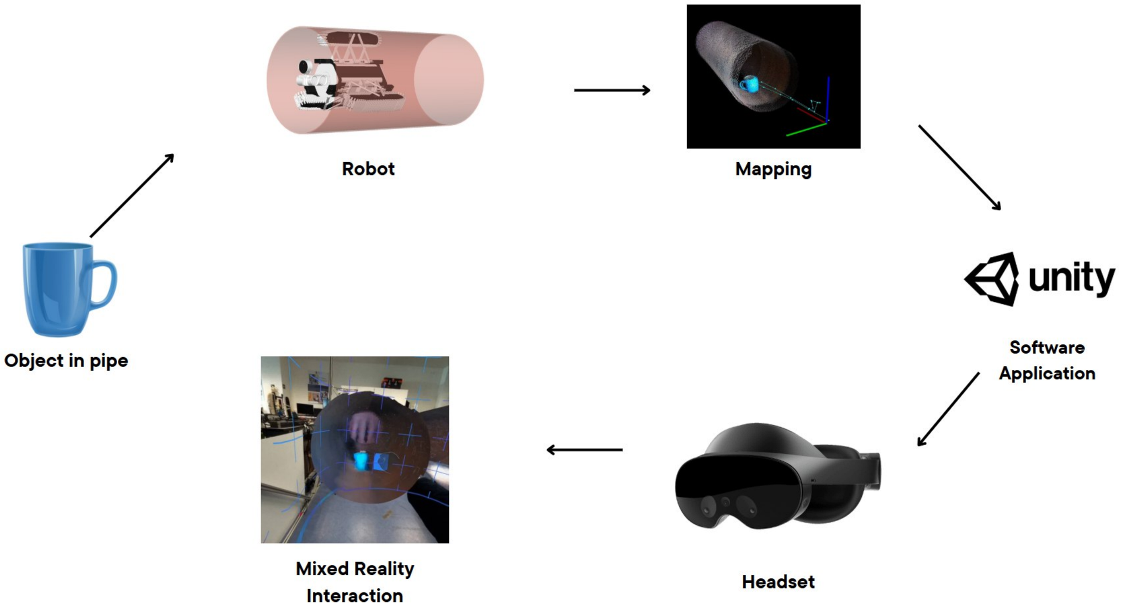


Figure 3.11: Calculating the motor angles

to ensure compatibility with 3D rendering engines. The finalized 3D model is imported into the Unity software application, where it is prepared for visualization. Using the MetaQuest headset, the user can interact with the reconstructed pipeline in mixed reality, allowing them to examine the object's position and surrounding area from different perspectives. This closed-loop system enables inspectors to seamlessly transition from real-world detection to virtual analysis, improving spatial awareness and decision-making during pipeline inspections.

Chapter 4: **Testing/Evaluation**

4.1 Inpipe garbage cleaning

In this section describes an experiment conducted to evaluate the In Pipe Robot's capability to clean garbage from within pipes. This scenario demonstrates the robot's ability to detect, grasp, lift, and remove debris, showcasing its potential to enhance pipeline maintenance operations.

The Fig. 4.1b shows different stages of the cleaning process. The robot navigates through the pipe using its three caterpillar tracks, positioned 120 degrees apart to provide stability and maneuverability.

- Navigation and Object Detection : The robot is maneuvered through the pipe using a control interface. The first-person view camera mounted on the end effector provides live feed to the operator, allowing them to detect objects inside the pipe. In this scenario, the target is a piece of debris.
- Approach and Grasp: Upon locating the debris, the operator adjusts the manipulator arm to approach the target. The end-effector is positioned to securely grasp the debris.
- Lifting the Debris: The manipulator arm lifts the debris. The lifting capability is dependent on the weight of the debris and the strength of the manipulator.
- Debris Removal: Once the debris is secured, the robot can transport it out of the pipe. The operator carefully navigates the robot back to the pipe entrance, where the debris is safely removed.

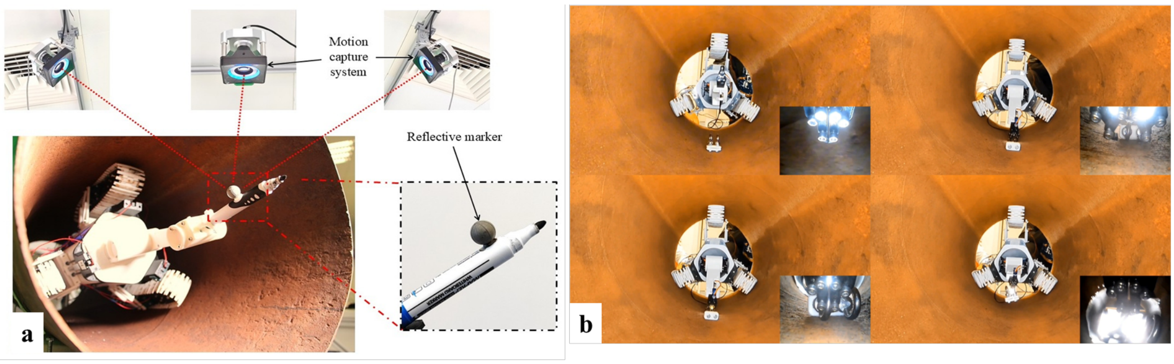


Figure 4.1: a)Experimental setup for pipe welding imitation process and b) debris removal

4.2 Inpipe repair work

In this experiment, the in-pipe robot was tasked with drawing a rectangle on the inner surface of a semi-cylinder. This task was designed to simulate operations such as welding, where precise control over the manipulator's movement is essential. The rectangular path was chosen as it requires the robot to perform linear movements in multiple directions—forward, backward, left, and right—while maintaining accuracy and consistency with previously drawn lines (see 4.1a).

The robot's manipulator was equipped with a drawing tool, and the task began with the robot positioning itself at the starting point of the rectangle. The manipulator then traced the rectangle by moving along the path. The experiment was aimed at demonstrating the robot's ability to accurately follow a complex path and return to previous points with high precision, which is crucial in tasks that require continuous and seamless operations like welding or cutting.

Throughout the process, the robot successfully demonstrated its capability to perform linear movements while maintaining alignment with the previously drawn lines. This not only showcased the precision of the manipulator but also highlighted the robot's potential in performing detailed and accuracy-critical tasks inside confined spaces like pipelines.

The sequence of images in Figure **??** illustrates the progression of the experiment:

- (a) and (b) show the initial positioning and the start of the drawing operation.
- (c) and (d) depict the manipulator moving to create the side and back lines of the rectangle.
- (e) highlights the final stages of completing the rectangle by connecting the lines.
- (f) shows the completed rectangle.

To accurately capture and analyze the movements of the In-pipe Robot during the experiment, a sophisticated motion capture system was employed (Fig.4.1). This system relied on high-precision camera optics to monitor the robot's actions in real time. A specialized motion capture marker was securely attached to the tip of the manipulator arm, serving as a reference point for the cameras.

As the robot executed this task, the cameras continuously tracked the motion capture marker. This allowed for the precise recording of the manipulator's position, orientation, and trajectory as it traced the intended path.

By incorporating this motion capture system, the experiment not only demonstrated the robot's capability to perform precise tasks but also provided a robust dataset for further development and optimization of the In Pipe Robot's performance in complex, accuracy-demanding operations.

4.3 AR inspection: Experimental Setup

To evaluate the performance of the inspection system, several objects were placed inside the pipeline to simulate potential anomalies or foreign items that could be encountered during real inspections. Figure 4.2 shows examples of the test setup, including a cup, a small box, and the Umnitsa inspection module positioned within the pipeline. These objects were strategically placed at different locations and orientations to assess the system's ability to detect, scan, and visualize them accurately. The robot was tasked with scanning the pipeline while capturing depth, RGB, and infrared data, which were later processed for visualization in the mixed reality environment. This testing scenario allowed us to verify both the detection accuracy and the effectiveness of the immersive visualization in identifying and localizing objects inside the pipeline.

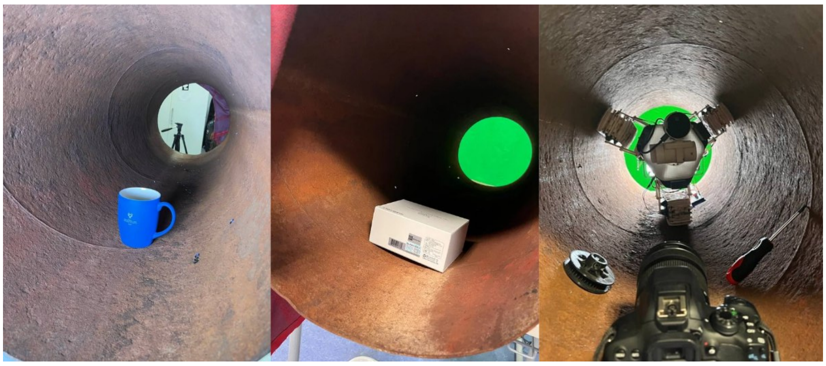


Figure 4.2: Placed objects

In addition to testing object detection inside the pipeline, further experiments were conducted to evaluate the system's ability to identify defects on the pipeline surface. Figure 4.3 shows the preparation for these tests. As shown in (a), an external flashlight was used to improve illumination inside the dark pipeline environment, ensuring that the camera could capture clear visual and depth data. Image (b) displays the pipeline with several small holes intentionally created to simulate defects. In (c), some of these holes were partially covered with replacement soil to assess whether the system could detect obscured or partially hidden anomalies. This setup allowed us to test the sensitivity and reliability of the inspection system under realistic and challenging conditions.

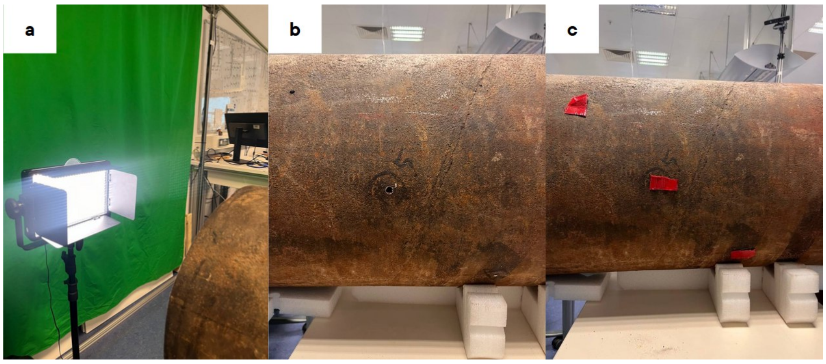


Figure 4.3: a) Flashlight for dark environment; b) prepared holes c) covered by tapes to replace soil

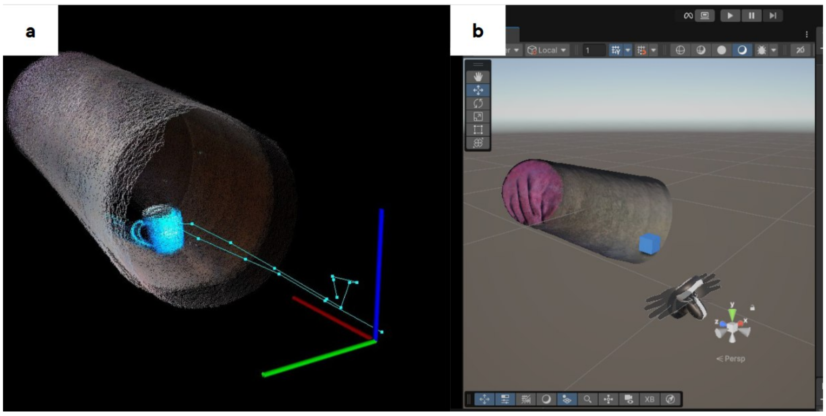


Figure 4.4: a) scanned pipe; b)Insertion to Unity

Following the scanning and defect detection experiments, the generated 3D data was processed and prepared for visualization. Figure 4.4 illustrates the resulting scanned pipeline and its integration into the visualization environment. In (a), the 3D scan of the pipeline, including the detected object (a cup), is shown as a point cloud with spatial axes for orientation. This scan was produced using RTAB-Map and subsequently converted into a mesh for further use. In (b), the scanned model was imported into Unity, where it was integrated into the mixed reality application. This allowed the inspection environment to be visualized within the headset, providing an interactive 3D representation of the pipeline interior for evaluation and analysis.

During the development process, we initially used the HoloLens 2 as the target mixed reality headset for visualization. However, we decided to switch to the MetaQuest Pro after evaluating several factors. The MetaQuest Pro offers a more mature and accessible development ecosystem, particularly for Unity-based projects, which allowed us to implement features and resolve technical issues more efficiently. Additionally, the deployment process on MetaQuest Pro was faster and required fewer steps compared to the HoloLens 2, reducing the overall testing and debugging time. From a performance perspective, the MetaQuest Pro provided improved mixed reality capabilities, including better hand tracking, more responsive rendering, and a larger field of view, enhancing the user experience during inspection tasks. This transition enabled us to accelerate development while achieving a higher-quality immersive visualization, aligning better with the goals of our inspection system.

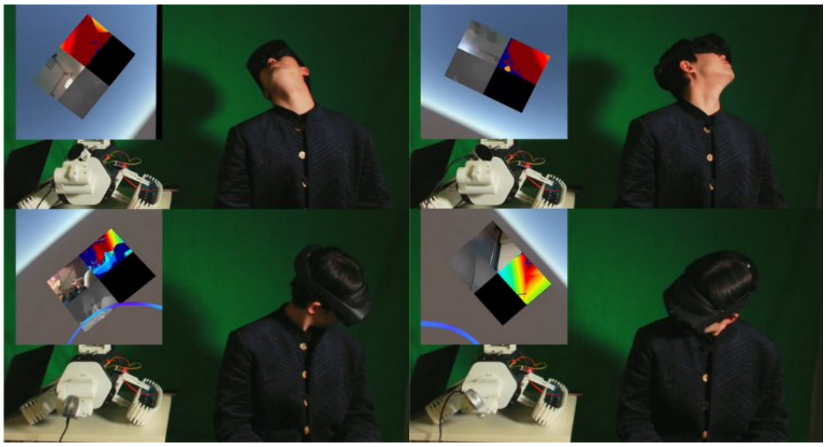


Figure 4.5: Testing the Master and Slave functionality

Figure 4.5 shows the testing of the Master and Slave functionality, demonstrating how head movements from the user (Master) are transmitted to control the orientation of the camera system (Slave). In this experiment, the user wears the MetaQuest Pro headset and moves their head in different directions while observing the real-time camera feed inside the virtual environment. The camera's pan and tilt motors respond to the user's gaze direction, replicating the head movements on the physical inspection device. The top row of images illustrates different head orientations and the corresponding changes in the visualization, while the bottom row shows additional viewing angles and data overlays displayed in the virtual scene. This testing validated the system's ability to synchronize the user's head movements with the camera's motion, achieving intuitive and responsive control for immersive pipeline inspection.

Chapter 5: **Results**

5.1 Manipulator end effector tracking

Two trajectories were tracked using Optitrack. The first manual trajectory served as the necessary trajectory for comparison, and the second was the actual trajectory of movement of the manipulator. As shown in plot (Fig.5.1 g), the discrepancy between the two graphs is clearly visible. This mismatch occurs due to the position of the marker, which is fixed slightly away from the edge of the drawing tool (Fig. 5.1 g). The consequence of placing the marker far from the edge of the tool is that it creates a lever arm effect, which leads to a discrepancy between the desired and actual trajectories. Despite the fact that both the tool and the marker rotate at the same angle, the radial distance from the axis of rotation to the marker leads to a smaller arc of movement compared to the edge of the tool. This leads to changes in both the radial and axial trajectories, which leads to a deviation of the recorded trajectory from the specified trajectory, reflecting the influence of this displacement.

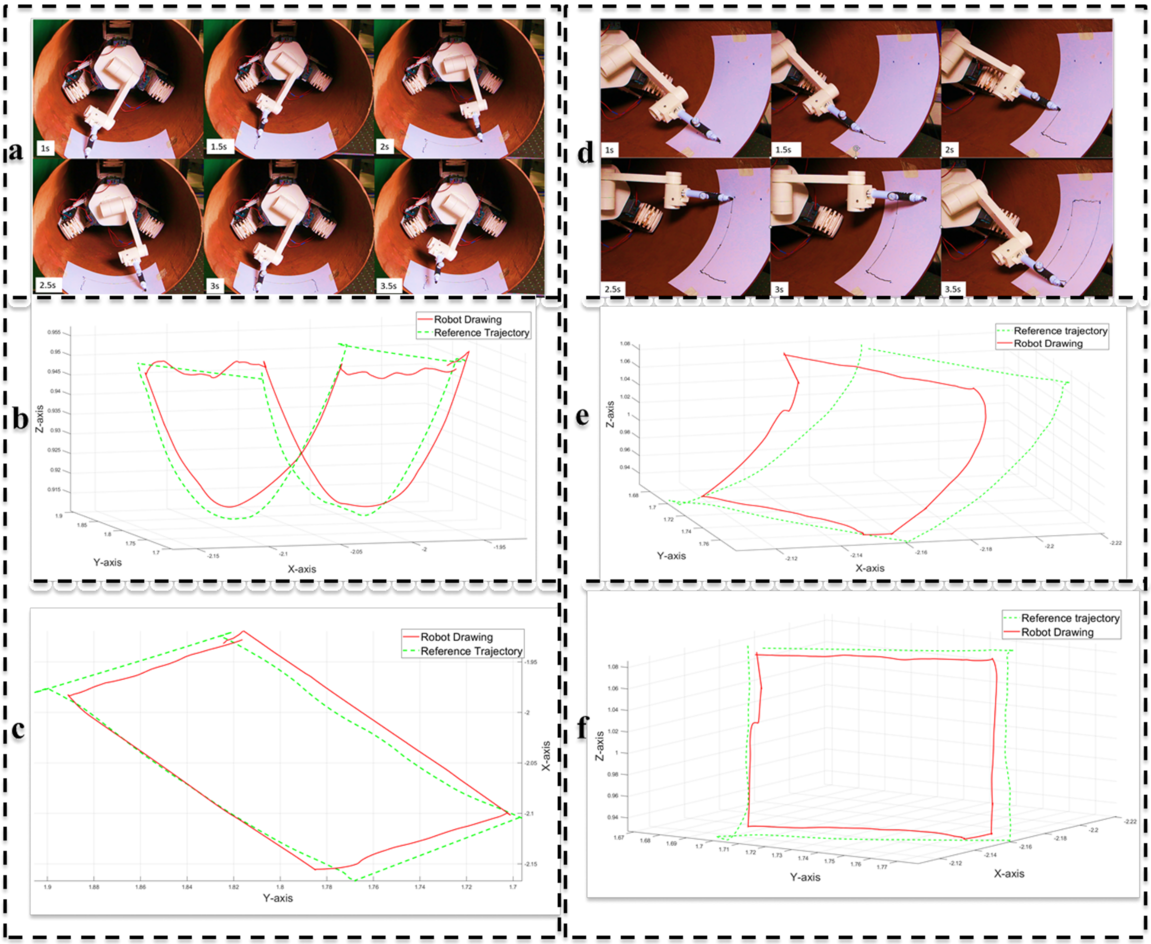


Figure 5.1: Experimental results of welding imitations. a) Bottom side drawing timeline. b) Bottom side drawing 3D trajectory plot. c) 2D drawing at the bottom side. d) Pipe side drawing experiment timeline. e) 3D trajectory plot. f) 2D plane view of side drawing plot.

5.2 Master/Slave and Anomaly detection

Figure 5.2 demonstrates the system in operation during robot deployment. The user controlled the robot using the MetaQuest Pro headset, receiving live depth, RGB, and infrared frames in the mixed reality interface. The images show synchronized control between the user's head movements and the robot's camera orientation, enabling real-time inspection and visualization inside the pipeline.

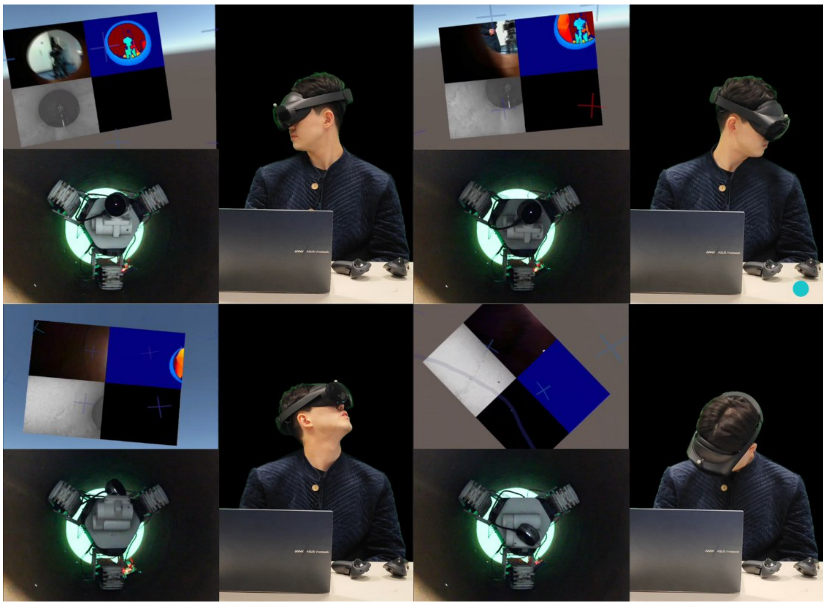


Figure 5.2: Sending the Robot

Figure 5.3 shows the testing of the anomaly detection algorithm integrated into the mixed reality interface. The green and red overlays in the visualizations represent detected surface features and highlighted anomalies, respectively. The user, wearing the MetaQuest Pro headset, observes these detection results in real time while controlling the inspection process. This evaluation demonstrated the system's ability to visualize detected anomalies directly within the immersive environment, enabling more intuitive identification of irregularities inside the pipeline.

During system testing, it was observed that the TCP communication could effectively handle uncompressed data transmissions of approximately 1–2 megabytes per frame without significant delays. However, transmitting raw image frames at this size resulted in low frame rates (around 0.4 FPS) and introduced latency that negatively affected other critical processes, such as motor angle calculations and system responsiveness. To address this issue, JPEG compression was implemented, reducing the data size by approximately 40 percent. This optimization resulted in each frame being compressed to around 25–35 kilobytes. As a result, the frame rate was significantly improved, increasing from 0.4 FPS to approximately 4 FPS. This compression allowed faster data transmission, reduced network load, and ensured that the communication channel did not bottleneck the real-time control loop, maintaining both smooth visualization and timely actuation.

Figure 5.4 showcases a key result from the anomaly detection system, where three small holes placed diagonally on the pipeline surface were successfully detected and visualized in the mixed reality interface. The detected anomalies are clearly marked in the virtual environment and correspond precisely to their physical locations on the actual pipeline, as indicated by the red arrows. This result demonstrates the accuracy of the detection algorithm and the effectiveness of the spatial mapping between the real pipeline and the virtual visualization.

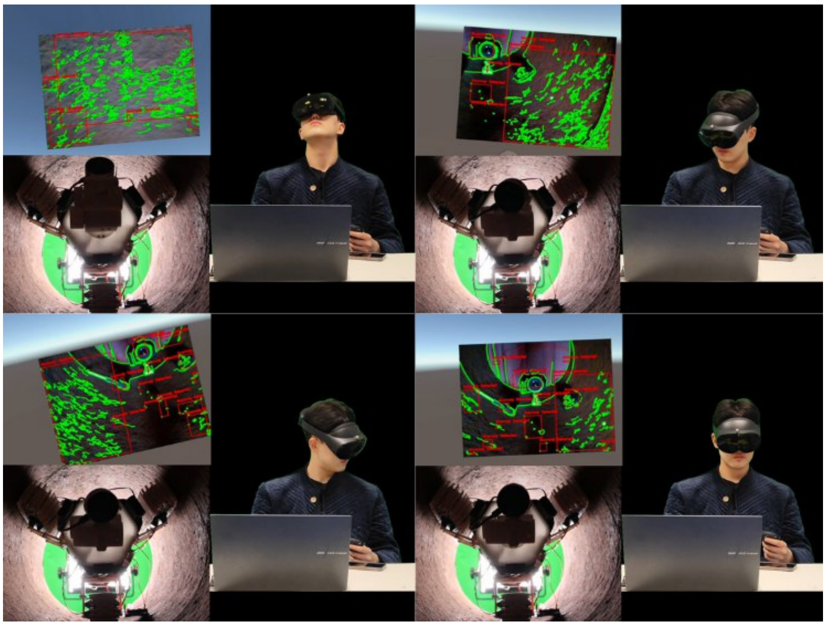


Figure 5.3: Anomaly detection algorithm

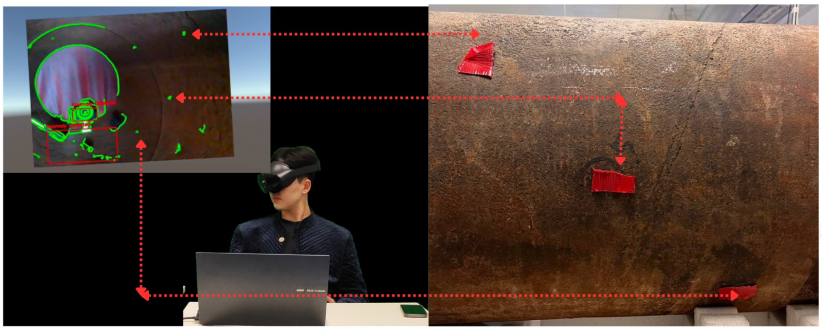


Figure 5.4: detected diagonally placed three holes

The user, wearing the MetaQuest Pro headset, was able to intuitively observe and verify the detected anomalies in real time. This experiment validated the system's capability to identify multiple defects across different positions on the pipeline surface, enhancing the inspector's situational awareness and decision-making process.

5.3 Mixed Reality Experience

After exporting the scanned pipeline map into Unity, the project was deployed to the MetaQuest Pro headset for augmented reality visualization. In Play mode, as shown in Figure 5.5, the user can interact with the virtual pipeline while still seeing the real-world surroundings. In (a), a virtual grabbable cube is placed inside the pipeline model, demonstrating the ability to insert and manipulate virtual tools within the scene. In Unity, the size of virtual objects can be adjusted to match real-world dimensions if the actual measurements are known, allowing for accurate referencing and comparison. This feature provides a valuable benefit by enabling users to estimate and compare the size of objects or defects relative to the real environment. Additionally, when visualizing long sections of pipeline, the user can intuitively understand the locations of detected debris, leftover tools, or other anomalies along the pipeline path, enhancing spatial awareness and inspection planning.

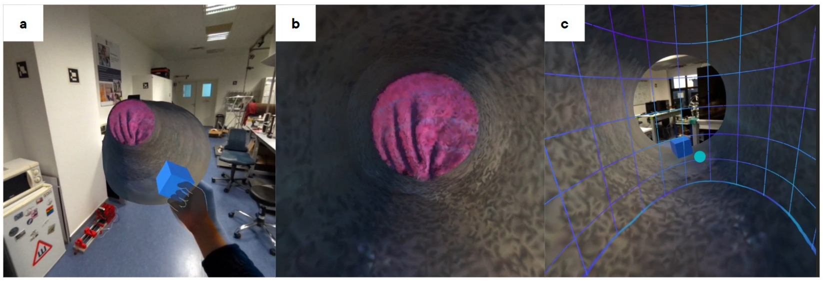


Figure 5.5: Pipe visualization in AR. a)playing with grabbable cube b)traveling forward th pipeline c)traveling back the pipeline

Figures 5.6 and 5.7 present the evaluation of the system's spatial accuracy by comparing the sizes of virtual objects with their corresponding scanned real-world counterparts inside the augmented reality environment. In Figure 5.6, the virtual grabbable cube was visually aligned and compared against the scanned test cube inside the pipeline model. Similarly, in Figure 5.7, the virtual grabbable cube was compared with the scanned cup placed inside the pipeline. By aligning the virtual and scanned objects, the system allowed the user to estimate object sizes, positions, and spatial relationships directly within the AR interface. This functionality demonstrates the potential of the system for referencing and verifying the scale of detected holes or objects relative to known sizes, providing an intuitive and interactive tool for inspection and assessment. However, detecting holes or small defects inside the pipeline proved to be challenging, as it depends on several factors including the stability of the camera, the movement of the robot, the computational demands of SLAM, and the lighting conditions inside the pipeline.

To further validate the accuracy of the virtual objects in relation to their real-world counterparts, a double-checking procedure was performed outside the pipeline environment, as shown in Figure 5.8. In (a), the virtual cube was visually aligned with the real cup and test cube within the augmented reality interface, while (b) shows the user physically placing the real test cube next to the virtual object for direct comparison. This step confirmed that the virtual objects maintained consistent scale and spatial relationships not only within the

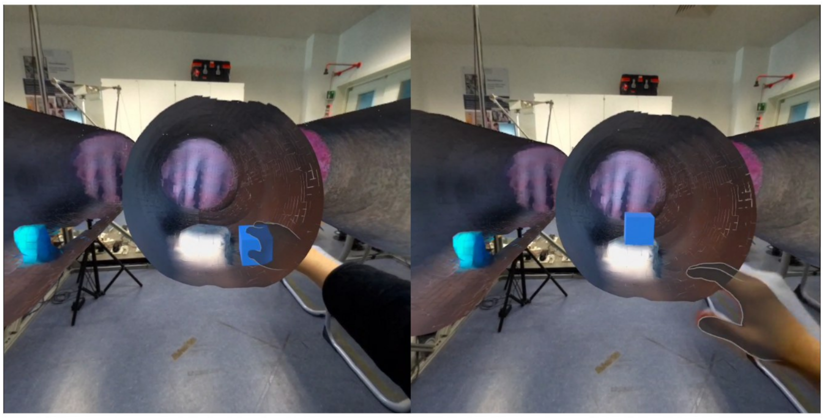


Figure 5.6: comparison of the virtual cube size with test cube size

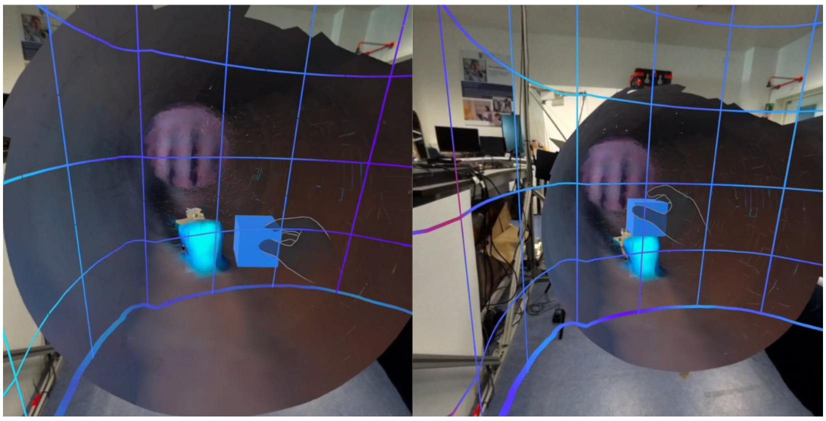


Figure 5.7: comparison of the virtual cup size with test cube size

scanned pipeline model but also in the external environment. This additional verification strengthened the confidence in the system's ability to represent detected objects accurately in augmented reality, supporting reliable referencing and interaction during inspection tasks.

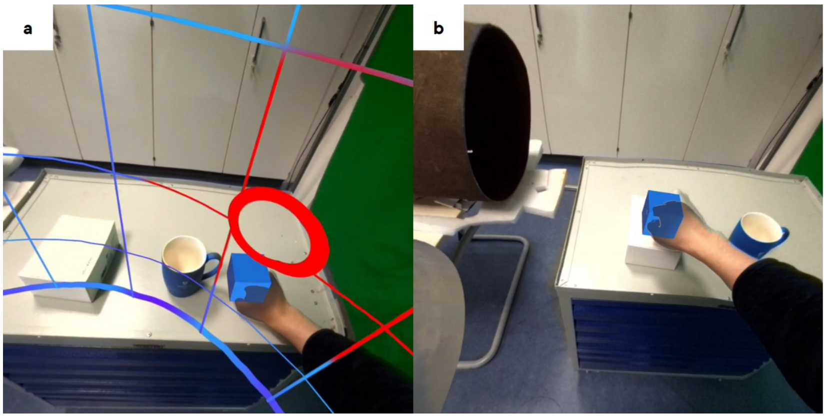


Figure 5.8: double-checking with real versions

Chapter 6: **Conclusions and Future Work**

This study introduced an innovative hybrid robot designed for both the inspection and maintenance of pipelines. A key feature of the robot is its customizable central block, which enables the integration of various inspection tools as well as a manipulator capable of simulating welding operations during maintenance tasks. The robot's multi-functional design expands its potential applications across industrial settings. Experimental results confirmed that the robot could successfully perform tasks typically handled by human operators, such as welding and debris removal. The primary aim of the research was to validate the integration of welding functionality within a confined pipe environment.

Looking ahead, a key objective is to incorporate haptic feedback technology to improve human-robot interaction, particularly for welding and repair activities. Furthermore, the robot's intuitive interface contributes to improved usability and work precision. Future work should also include real-world testing to assess the feasibility and performance of plasma welding within operational pipeline conditions.

In addition to the robot's physical functionality, this study demonstrated the integration of immersive visualization using mixed reality to enhance pipeline inspection and maintenance tasks. By leveraging an augmented reality interface, the system enabled immersive spatial awareness, allowing operators to intuitively explore the pipeline environment without relying on traditional flat screens or 2D displays. This immersive approach reduced the user's cognitive load and provided a more natural interaction, where the operator's eyes and head movements directly controlled the camera perspective, eliminating the need for external joysticks or keyboard input.

Furthermore, an integrated anomaly detection algorithm assisted the operator by highlighting potential defects in real time. While the system was capable of detecting deformations, holes, and other surface irregularities, the detection accuracy was found to depend heavily on factors such as camera stability, SLAM performance, robot movement, computational capacity, and lighting conditions.

A key advantage of the system was the ability to export the scanned 3D pipeline maps into Unity for further analysis. When the real-world dimensions of the pipeline were known, these virtual models could be accurately scaled, enabling virtual objects—such as the grabbable cube used in testing—to serve as size references. This capability allows inspectors and maintenance teams to assess whether specific tools or replacement parts will fit within the pipeline's confined spaces before on-site intervention. Additionally, the system supports remote validation of pipe size and geometry by comparing the current scanned conditions with a baseline model.

Beyond inspection, the mixed reality interface provides valuable training opportunities by allowing workers to rehearse maintenance procedures in a safe, immersive environment. Trainees can practice identifying defects, selecting tools, and planning repair strategies while visualizing real pipeline configurations, ultimately reducing risks associated with confined or hazardous workspaces.

Future work will focus on improving the mechanical and tracking components of the system, including replacing the current motors with smoother actuators and integrating OptiTrack technology to enhance the positional tracking of the Umnitsa's end effector. Additional experimental comparisons are planned, along with expanded computational and qualitative analyses of the system's detection accuracy across various test cases. Future improvements to the anomaly detection algorithm will also explore its application in more diverse pipeline conditions.

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