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«Design of a control system for an in-pipe mobile robot and diagnostics of the condition of pipes»

МАГИСТРЛІК ДИССЕРТАЦИЯ

7M07107 – Робототехника және мехатроника

Алматы 2023

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Диссертацияның атауы: «Design of a control system for an in-pipe mobile robot and diagnostics of the condition of pipes»
Дайындау бағыты: 7M07107 – Робототехника және мехатроника

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Магистрант Даниялов Мадияр Саятұлы
Тақырыбы: Design of a control system for an in-pipe mobile robot and diagnostics of the condition of pipes
Университет ректорының 2021ж. «29» 10 №1753-м бұйрығымен бекітілген
Аяқталған жұмысты тапсыру мерзімі: «31» маусым 2023 ж.
Магистрлік диссертацияның бастапқы деректері:.
Магистрлік диссертацияда қарастырылатын мәселелер тізімі:
а) Control approaches for in-pipe robots
б) Diagnostis of pipe conditions
в) System architecture of control and diagnostics methods
Графикалық материалдың тізімі (міндетті сызбаларды дәл көрсете отырып):
жұмыс презентациясы слайтарда 12 көрсетілген
Ұсынылатын негізгі әдебиеттер: 19 әдебиеттер тізімі және__қосымша

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КЕСТЕСІ

Бөлімдер атауы, әзірленетін сұрақтар тізбесі	Ғылыми жетекшіге ұсыну мерзімдері	Ескерту
Control approaches for in-pipe robots	16.01.2023	Орындалды
Diagnostics of pipes	13.02.2023	Орындалды
System architecture	09.03.2023	Орындалды
Robot's fit in the pipe	17.03.2023	Орындалды
Configuration of the robot	18.04.2023	Орындалды
Қорытынды бөлім	22.05.2023	Орындалды

Аяқталған магистрлік диссертация үшін, оған қытысты бөлімдердегі диссертациялар кеңесшілері мен қалып бақылаушының
қолдары

Бөлімдердің атауы	Кеңесшілер, тегі, аты, әкеснің аты, (ғылыми дәрежесі, атағы)	Қол қойылған күні	Қол
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LIST OF ABBREVIATIONS

CAD – Computer - aided design
TOF Time-of-Flight
DCDirect current
SCC – Stress corrosion cracking
ROV – Remotely operated vehicl
UT – Ultrasonic testing
MFL – Magnetic Flux Leakag
LIDAR – Light Detection and Ranging
PIG – Pipe inspection gauge robot

ABSTRACT

The objective of this dissertation is to develop a system for motion and diagnostics in an in-pipe robot using TOF (Time-of-Flight) sensor and LIDAR camera methods for pipe condition diagnosis. The research aims to address the challenges of accurately assessing pipe conditions, including corrosion levels, blockages, and structural integrity.

The proposed system integrates TOF sensors and LIDAR cameras into the in-pipe robot to enable comprehensive pipe inspection. The TOF sensors utilize the principle of measuring the time it takes for a light signal to travel to an object and back, providing precise distance measurements. This information can be used to assess pipe dimensions, identify blockages, and detect abnormalities. The LIDAR cameras employ laser technology to generate detailed 3D maps of the pipe interior. These maps enable the detection of corrosion, cracks, and other defects, providing valuable insights into the pipe's condition.

The motion system of the robot allows it to navigate through pipes of various sizes and shapes. It incorporates the use of caterpillar tracks and adaptive mechanisms, ensuring smooth movement even in challenging pipe environments with bends and uneven surfaces. The motion system is designed to be stable, flexible, and adaptable to different pipe conditions.

The diagnostic system utilizes the data collected from the TOF sensors and LIDAR cameras to assess the pipe's condition. Advanced algorithms and image processing techniques are employed to analyze the collected data and identify potential issues such as corrosion, blockages, or structural weaknesses. The system provides accurate and real-time feedback on the pipe's health, enabling proactive maintenance and preventing costly failures.

The research methodology involves designing a wall-mounted robot capable of vertical and horizontal movement along pipes, including navigating bends. The robot consists of four modules, including a fixed main block and three moving parts. The movable modules are equipped with caterpillar tracks for longitudinal movement inside the pipe and adjusting to different pipe dimensions.

The robot's propulsion system utilizes a 25 rpm DC gear motor connected to wheels and driving belts, ensuring stability and alignment within the pipe. The main module houses a control unit and spring-loaded modules, increasing the robot's flexibility and enhancing friction with the pipe wall.

Overall, this dissertation aims to contribute to the field of in-pipe robotics by developing a comprehensive system for motion and diagnostics. The integration of TOF sensors and LIDAR cameras enhances the capabilities of the robot, enabling accurate and efficient pipe condition assessment. The research combines principles of robotics, sensor technology, and data analysis to provide an innovative solution for pipe inspection and maintenance.

АННОТАЦИЯ

Целью данной диссертации является разработка системы движения и диагностики внутритрубного робота с использованием датчика TOF (Time-of-Flight) и методов камеры LIDAR для диагностики состояния трубы. Исследование направлено на решение проблем, связанных с точной оценкой состояния труб, включая уровни коррозии, засорения и структурную целостность.

Предлагаемая система интегрирует датчики TOF и камеры LIDAR во внутритрубного робота, чтобы обеспечить всестороннюю инспекцию труб. Датчики TOF используют принцип измерения времени, необходимого световому сигналу для прохождения до объекта и обратно, обеспечивая точное измерение расстояния. Эта информация может быть использована для оценки размеров трубы, выявления засоров и обнаружения отклонений от нормы. В камерах LIDAR используется лазерная технология для создания подробных трехмерных карт внутренней части трубы. Эти карты позволяют обнаруживать коррозию, трещины и другие дефекты, обеспечивая ценную информацию о состоянии трубы.

Система движения робота позволяет ему перемещаться по трубам различных размеров и форм. Он включает в себя использование гусениц и адаптивных механизмов, обеспечивающих плавное движение даже в сложных условиях трубы с изгибами и неровными поверхностями. Система движения спроектирована так, чтобы быть стабильной, гибкой и адаптируемой к различным условиям трубопровода. Система диагностики использует данные, полученные от датчиков TOF и камер LIDAR, для оценки состояния трубы. Передовые алгоритмы и методы обработки изображений используются для анализа собранных данных и выявления потенциальных проблем, таких как коррозия, засоры или структурные недостатки. Система обеспечивает точную обратную связь в режиме реального времени о состоянии трубы, что позволяет проводить упреждающее техническое обслуживание и предотвращать дорогостоящие сбои.

Методология исследования предполагает создание внутритрубного робота, способного перемещаться по трубам вертикально и горизонтально, в том числе по изгибам. Робот состоит из четырех модулей, включая неподвижный основной блок и три подвижные части. Подвижные модули оснащены гусеницами для продольного перемещения внутри трубы и подгонки под различные размеры трубы.

В двигательной системе робота используется редукторный двигатель постоянного тока с частотой вращения 25 об/мин, соединенный с колесами и приводными ремнями, что обеспечивает устойчивость и выравнивание внутри трубы. В основном модуле находится блок управления и подпружиненные модули, повышающие гибкость робота и усиливающие трение о стенки трубы.

В целом, эта работа направлена на то, чтобы внести свой вклад в область внутритрубной робототехники путем разработки комплексной системы для движения и диагностики. Интеграция датчиков TOF и камер LIDAR расширяет возможности робота, обеспечивая точную и эффективную оценку состояния трубы. Исследование сочетает в себе принципы робототехники, сенсорных технологий и анализа данных, чтобы предоставить инновационное решение для проверки и обслуживания труб.

АҢДАТПА

Бұл диссертациялық жұмыстың мақсаты TOF (Time-of-Flight) сенсорын және құбыр жағдайын диагностикалау үшін LIDAR камера әдістерін қолдана отырып, құбыр ішіндегі роботта қозғалыс пен диагностика жүйесін жасау болып табылады. Зерттеу коррозия деңгейлерін, бітелулерді және құрылымдық тұтастықты қоса алғанда, құбыр жағдайларын дәл бағалау мәселелерін шешуге бағытталған.

Ұсынылған жүйе құбыр ішіндегі роботқа TOF сенсорлары мен LIDAR камераларын біріктіреді, бұл құбырларды жан-жақты тексеруге мүмкіндік береді. TOF сенсорлары қашықтықты дәл өлшеуді қамтамасыз ететін жарық сигналының объектіге және кері өтуіне кететін уақытты өлшеу принципін пайдаланады. Бұл ақпаратты құбыр өлшемдерін бағалау, бітелулерді анықтау және ауытқуларды анықтау үшін пайдалануға болады. LIDAR камералары құбыр интерьерінің егжей-тегжейлі 3D карталарын жасау үшін лазерлік технологияны пайдаланады. Бұл карталар коррозияны, жарықтар мен басқа да ақауларды анықтауға мүмкіндік береді, бұл құбырдың жай-күйі туралы құнды түсініктер береді.

Роботтың қозғалыс жүйесі оған әртүрлі өлшемдер мен пішіндегі құбырлар арқылы өтуге мүмкіндік береді. Ол иілу және тегіс емес беттері бар қиын құбыр орталарында да тегіс қозғалысты қамтамасыз ететін шынжыр табанды жолдар мен бейімделгіш механизмдерді пайдалануды қамтиды. Қозғалыс жүйесі тұрақты, икемді және әртүрлі құбыр жағдайларына бейімделетін етіп жасалған.

Диагностикалық жүйе құбырдың жағдайын бағалау үшін TOF сенсорлары мен LIDAR камераларынан жиналған деректерді пайдаланады. Жиналған деректерді талдау және коррозия, бітелу немесе құрылымдық әлсіздіктер сияқты ықтимал мәселелерді анықтау үшін кеңейтілген алгоритмдер мен кескінді өңдеу әдістері қолданылады. Жүйе құбырдың денсаулығы туралы нақты және нақты уақыт режимінде кері байланысты қамтамасыз етеді, бұл алдын ала техникалық қызмет көрсетуге мүмкіндік береді және қымбат тұратын ақаулардың алдын алады.

Зерттеу әдістемесі құбырлар бойымен тік және көлденең қозғалысқа қабілетті қабырғаға орнатылатын роботты жобалауды қамтиды, оның ішінде навигациялық иілулер. Робот төрт модульден тұрады, оның ішінде бекітілген негізгі блок пен үш жылжымалы бөлік бар. Жылжымалы модульдер құбырдың ішінде бойлық қозғалысқа және әртүрлі құбыр өлшемдерін реттеуге арналған шынжыр табанды жолдармен жабдықталған.

Роботтың қозғаушы жүйесі дөңгелектер мен жетекші белдіктерге қосылған 25 айн/мин тұрақты ток беріліс қозғалтқышын пайдаланады, бұл құбырдағы тұрақтылық пен туралауды қамтамасыз етеді. Негізгі модульде роботтың икемділігін арттыратын және құбыр қабырғасымен үйкелісті арттыратын басқару блогы мен серіппелі модульдер бар.

Тұтастай алғанда, бұл диссертация қозғалыс пен диагностиканың кешенді жүйесін жасау арқылы құбыр ішіндегі робототехника саласына үлес қосуға бағытталған. TOF сенсорлары мен LIDAR камераларының интеграциясы құбырдың жағдайын дәл және тиімді бағалауға мүмкіндік беретін роботтың мүмкіндіктерін арттырады. Зерттеу құбырларды тексеру және техникалық қызмет көрсету үшін инновациялық шешімді қамтамасыз ету үшін робототехника, сенсорлық технология және деректерді талдау принциптерін біріктіреді.

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INTRODUCTION

The primary objective of designing robots is to minimize human involvement in physically demanding and hazardous work environments. They are particularly useful in exploring inaccessible areas that are typically off-limits to humans. The intricate internal structure and potential dangers associated with pipes necessitate the use of robots for inspection purposes. Neglecting pipe inspection can lead to severe industrial accidents, causing environmental pollution and loss of life.

The inspection of such pipes requires robots to assess various aspects, including the level of pipe corrosion, extraction of usable components from within the pipe, and sampling of sludge and scale buildup on the pipe's interior. This dissertation focuses on the design of a novel in-line inspection robot. The design process involves design of a control system, kinematic and dynamic analysis of a crawler-type robot and diagnostics of the condition of pipes.

Kinematic calculations are employed to determine the robot's trajectory and analyze its movement in both straight and curved pipelines. By studying the dynamic equation of the robot, the impact of factors such as friction force, drag force, and robot mass on the robot's work and movement is analyzed. This analysis helps establish the minimum motor torque required for the robot to operate effectively in horizontal, inclined, and vertical pipelines.

A physical prototype of the proposed robot is developed using 3D printing technology, ensuring a solid-state structure. The prototype is then assembled for further evaluation. Motion simulation and experimental studies are conducted using this robot model to assess its performance and validate its functionality.

Diagnostics of the condition of pipes includes checking for geometry changes and unnatural irregularities on the surface of the pipe walls, machine vision to identify defects such as corrosion and cracks.

The mechanical design of the proposed in-line inspection robot was carefully developed to enable its movement within a 250 mm diameter pipe. The dimensions of the robot were determined to be a width of mm, a height of 300 mm, and a length of 290 mm. Figure 1 illustrates a 3D computer-aided design (CAD) model of the robot, consisting of four modules - a central module and three identical outer modules positioned 120 degrees apart from each other.

The central module houses essential components, including a video surveillance camera, a flashlight for dark environments, and electronic elements for the robot's control and monitoring system. On the other hand, the external modules incorporate motors and drive belts that facilitate the lateral movement of the robot. A passive linkage mechanism connects each module to the central module, enabling independent vertical movement of the modules. This mechanism ensures that the robot remains flexible enough to traverse the pipeline walls effectively. Moreover, it guarantees continuous contact between the moving modules and the pipeline walls throughout the inspection process.

To enhance the robot's grip and maintain contact with the pipe walls, compression springs are utilized. These springs apply a compressive force, enhancing the robot's stability and adherence to the pipe walls.

The objectives of an in-line robot are closely tied to the specific application and task at hand. The primary requirement for an in-line robot is to have the capability to explore its designated task area comprehensively. While existing robots have demonstrated successful navigation in horizontal pipelines, only a limited number of them are equipped to handle complex pipeline configurations such as vertical pipelines, elbows, and branching points.

The ability to move up and down the pipeline is important for the efficient operation of in-line robots. Thus, the ability to maneuver in such complex configurations is of great importance for the successful execution of embedded robots.

1 Problems of in-pipe diagnostics

1.1 Limited maneuverability in pipe configurations

The problem is the difficulty faced by in-pipe robots in adapting to various pipe configurations, including bends, junctions, and narrow passages, which restricts their ability to efficiently inspect and maintain pipelines.

The issue at hand revolves around the constrained maneuverability that robots encounter when navigating through diverse pipe configurations. These configurations encompass a range of obstacles, such as bends, junctions, and narrow passages, which pose significant challenges to the efficient operation of in-pipe robots. Their ability to adapt and traverse these complex pipe layouts is limited, hindering their capacity to carry out thorough inspections and perform maintenance tasks effectively.

One of the primary obstacles faced by in-pipe robots is maneuvering around bends in the pipeline. Bends can vary in angles and curvature(Fig. 1), requiring the robot to possess advanced navigation capabilities to negotiate these tight turns. The restricted space within the curved sections poses difficulties in maintaining stability, preventing the robot from smoothly progressing through the pipeline and potentially leading to navigation errors or even getting stuck.

Figure 1.1 - Different types of bends in the pipeline.

Another obstacle lies in the presence of junctions, where multiple pipes intersect. The robot needs to accurately detect and navigate these junctions, making decisions on which path to follow. The complexity increases as the number of interconnected pipes grows, further impeding the robot's ability to efficiently inspect and maintain the pipeline. The limited maneuverability in these intricate pipe configurations hampers the robot's productivity and may result in incomplete inspections or missed maintenance tasks.

Figure 1.1.1 – Junction of plastic sewer pipes

Additionally, narrow passages within the pipeline present a considerable challenge for in-pipe robots. These sections often restrict the size and mobility of the robot, making it difficult to pass through or access certain areas. The limited space not only affects the robot's ability to navigate but also limits its capacity to carry necessary equipment or sensors, potentially compromising the effectiveness of inspections or maintenance operations.

Addressing the issue of limited maneuverability in pipe configurations is crucial for enhancing the capabilities of in-pipe robots. Research and development efforts are focused on designing a robot with improved mobility, adaptability to overcome these challenges. Advanced sensing technologies, such as 3D imaging, can provide the robot with a better understanding of the pipe layout, allowing it to navigate bends, junctions, and narrow passages more efficiently. Furthermore, in the future, advancements in robotics algorithms and artificial intelligence can enable robots to make real-time decisions, optimizing their movement in response to different pipe configurations.

By improving the maneuverability of in-pipe robot and enhancing. adaptability to diverse pipe layouts, the efficiency and effectiveness of pipeline inspections and maintenance can be significantly enhanced, reducing costs, minimizing downtime, and ensuring the integrity and safety of the pipeline infrastructure.

1.2 Limited adaptability to pipe conditions

The current challenge lies in the incapacity of existing in-pipe robots to adjust to diverse pipe conditions, including changes in pipe diameter, surface texture, and the presence of debris or sediment. These variations significantly impact the robots' ability to move and perform effectively within the pipes.

The issue at hand revolves around the limited adaptability of current in-pipe robots to various pipe conditions, which encompasses a range of factors such as variations in pipe diameter, surface roughness, and the presence of debris or sediment. These conditions pose significant challenges to the locomotion and overall performance of in-pipe robots, hindering their effectiveness in inspection and maintenance operations.

Figure 1.2 – Presencse of debris and rust in pipe

One of the primary challenges arises from variations in pipe diameter. Pipes can have different sizes and dimensions, ranging from larger diameters to narrow passages. In-pipe robots must be able to adapt to these variations to ensure successful traversal through the pipeline. Limited adaptability to different pipe diameters can result in robots getting stuck or facing difficulties in movement, impeding their ability to effectively inspect and maintain the pipeline infrastructure.

Another factor that affects the adaptability of in-pipe robots is the surface roughness of the pipes. Pipe surfaces can vary in texture, ranging from smooth to rough or even corroded. The robots must be capable of navigating these rough surfaces to maintain stable locomotion and prevent slippage. However, the lack of adaptability to different surface conditions can lead to compromised traction and stability, reducing the robot's efficiency and potentially causing damage to the pipeline or the robot’s driving modules, for example, the dc motor can overheat due to the fact that it will constantly spin at high efforts.

The presence of debris or sediment within the pipes is yet another challenge that limits the adaptability of in-pipe robots. Pipes can accumulate various forms of debris, including sediment, rust, or other foreign objects, which can hinder the robot's movement or obstruct its sensors. Robots must possess the capability to navigate through such environments and effectively avoid obstacles. Failure to adapt to these conditions can result in reduced inspection coverage, compromised data collection, and even equipment damage.

Addressing the issue of limited adaptability to pipe conditions requires advancements in robot design, sensor technology, and control algorithms. Research efforts are focused on developing robot with versatile locomotion mechanisms that can adjust to variations in pipe diameter, such as using modular or flexible components. Additionally, the integration of advanced sensors, such as 3D scanners and TOF sensors, can enhance the robot's ability to perceive and adapt to different surface roughness conditions. Furthermore, in the future, the development of intelligent algorithms that can analyze and interpret sensor data in real-time can enable the robots to make informed decisions and navigate through debris-laden pipes more effectively.

By improving the adaptability of in-pipe robots to various pipe conditions, the efficiency and effectiveness of pipeline inspection and maintenance can be significantly enhanced. Robot capable of seamlessly adjusting to changes in diameter, surface roughness, and the presence of debris or sediment will be better equipped to navigate and perform their tasks in a wide range of pipe conditions. This, in turn, will result in more thorough inspections, timely maintenance, and improved pipeline integrity.

1.3 Imprecise navigation and localization

The challenge lies in the absence of precise navigation and accurate localization techniques for in-pipe robots, which results in inaccuracies in their positioning and movement within the pipeline network.

The issue at hand revolves around the imprecise navigation and localization experienced by in-pipe robots, which can have detrimental effects on their positioning and movement within the pipeline system. Currently, efforts are being made to address this challenge by incorporating advanced technologies such as gyroscopes to provide a better understanding of the robot's position in the pipe.

One method employed to enhance navigation and localization involves the utilization of x, y, z gyroscopes. These gyroscopes measure the angular velocity of the robot's movement, allowing for a more accurate assessment of its position within the pipe. By capturing data on rotational movements along the three axes (x, y, z), the gyroscope provides valuable information that aids in determining the robot's orientation and position.

The x-axis of the gyroscope indicates the rotational movement around the horizontal axis, the y-axis represents the rotational movement around the vertical axis, and the z-axis captures the rotational movement around the longitudinal axis. By analyzing the data from the gyroscopes, it becomes possible to ascertain the robot's current position, its orientation relative to the pipe, and any deviations from the desired trajectory.

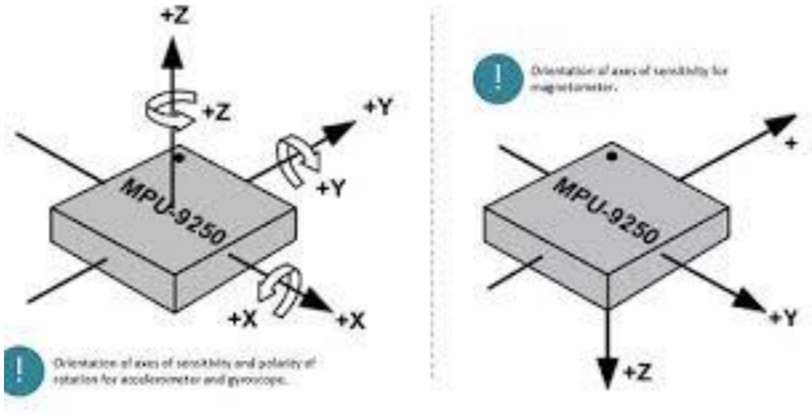

Figure 1.3 – GY521 mounted on a robot

Implementing gyroscopes for navigation and localization in in-pipe robots offers several advantages. Firstly, it enables a more precise understanding of the robot's movement within the pipe system, minimizing errors in its positioning. This enhanced accuracy aids in avoiding collisions with pipe walls, obstacles, or other components, ultimately preventing damage to the robot and the pipeline infrastructure.

Furthermore, the gyroscope data can be combined with other sensor information, such as accelerometers and odometers, to create a comprehensive localization system.

Additionally installed a speedometer based on a Hall sensor and a magnet. This fusion of sensor data helps to compensate for any limitations or uncertainties in individual sensors, providing a more reliable and robust position estimation for the robot.

Efforts are also being made to develop sophisticated algorithms that can process the gyroscope data in real-time, enabling the robot to make autonomous adjustments to its movement and maintain precise positioning. These algorithms can take into account factors such as drift or noise in the gyroscope measurements, ensuring the accuracy and stability of the robot's navigation.

By leveraging x, y, z gyroscopes and integrating them into navigation and localization systems, in-pipe robots can overcome the limitations of imprecise positioning and movement. This advancement enhances their ability to perform inspections, maintenance tasks, and repairs within pipelines with a higher degree of accuracy and efficiency. As a result, the integrity and reliability of the pipeline infrastructure can be maintained, reducing the risk of failures and improving overall operational performance.

1.4 Integration of sensor data and control algorithms

The next issue at hand is the inadequate integration and utilization of sensor data and control algorithms in the control systems of in-pipe robots, which leads to suboptimal decision-making and performance.

The issue at hand is the ineffective integration of sensor data and control algorithms within the control systems of in-pipe robots. However, efforts are being made to address this challenge by utilizing an Arduino-based Time-of-Flight (TOF) sensor mounted at the center of the robot. This sensor rotates 360 degrees in both forward and backward directions, with the data being printed on a communication port (comport) and subsequently transmitted to Python for further processing. In Python, the collected data is utilized to plot a polar graph, providing a visual representation of the in-pipe environment at a single rotation.

The integration of an Arduino-based TOF sensor with the in-pipe robot allows for the collection of precise distance measurements from the surrounding pipe walls and other objects within the pipeline. By rotating the sensor 360 degrees, a comprehensive view of the pipe's interior is obtained, enabling the robot to gather detailed spatial information.

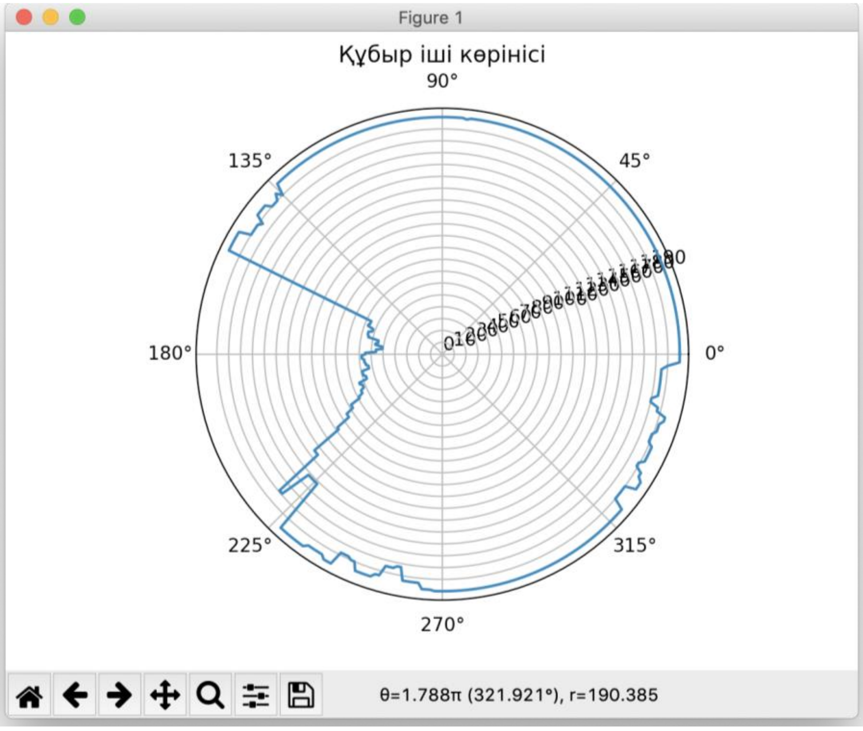

Figure 1.4 – Visualization of pipe's internal structure.

The collected sensor data is then transmitted to Python for processing and visualization. Python, being a versatile programming language with robust data analysis and plotting capabilities, is utilized to plot a polar graph based on the received data. This polar graph offers a clear and intuitive representation of the pipe's internal structure, allowing operators or automated systems to easily interpret the environment.

The utilization of this integrated system, comprising the Arduino-based TOF sensor, the data transmission via comport, and the data processing and visualization in Python, addresses the problem of ineffective integration of sensor data and control algorithms. It enables seamless communication between the hardware sensor and the software control system, facilitating the utilization of real-time data for decision-making and performance optimization.

By leveraging this integrated approach, in-pipe robots can effectively navigate through the pipeline, avoiding obstacles and making informed decisions based on the precise distance measurements provided by the TOF sensor. The visualization of the collected data through the polar graph enhances situational awareness and enables operators to quickly identify potential issues or anomalies within the pipe. The integration of an Arduino-based TOF sensor, data transmission via comport, and data processing and visualization in Python represents a significant step towards overcoming the challenge of ineffective integration of sensor data and control algorithms in in-pipe robots. This integrated system enhances the robot's perception of the environment, facilitates better decision-making, and improves overall performance during inspection and maintenance operations within pipelines.

The Time-of-Flight (ToF) sensor measures the distance or range to an object by calculating the time taken for a light or sound signal to travel to the object and back. The formula to calculate the distance measured by a ToF sensor is as follows:

$$d = c \times \frac{t}{2}, \tag{2.1}$$

where d – distance between the object and sensor, m;

c – speed of light, m/s.

"Speed of Light" refers to the speed at which the signal travels, which depends on the medium being used. In the case of light, the speed of light in vacuum is approximately 299,792,458 meters per second (m/s)..

"Time" represents the time it takes for the signal to travel to the object and back. Since the ToF sensor measures the round-trip time, it is divided by 2 to obtain the one-way distance.

By multiplying the speed of light by half of the measured time possible to calculate the distance to the object as detected by the ToF sensor.

2 Control Approaches for In-Pipe Robots

Developing effective control approaches is crucial for enabling precise and efficient movement of in-pipe robots. Several control strategies have been explored to address the unique challenges encountered in pipe environments.

One common control approach is the use of model-based control techniques. These techniques involve developing mathematical models of the robot and the pipe environment to simulate and optimize its motion. Model-based control enables accurate positioning, trajectory planning, and obstacle avoidance, enhancing the robot's ability to navigate through complex pipe configurations.

Another approach is behavior-based control, which focuses on integrating multiple behavior modules to achieve desired robot behaviors. Each behavior module is responsible for a specific task or action, such as turning, climbing, or maintaining a certain distance from the pipe walls. By combining these modules based on sensory inputs and control signals, behavior-based control enables flexible and adaptive robot movements in response to the pipe's characteristics.

Ultimately, the choice of control approach depends on factors such as the specific task requirements, robot design, available sensors, and the complexity of the pipe environment. Combining multiple control strategies and leveraging advancements in machine learning and artificial intelligence can lead to more robust and intelligent control approaches for in-pipe robots, enhancing their performance and expanding their capabilities in various applications.

3 Challenges and Limitations

Despite their potential and advancements, in-pipe robots still face certain challenges and limitations that need to be addressed for wider adoption and improved performance.

The power and energy requirements for in-pipe robots also present limitations. Operating within pipes often requires compact and lightweight designs, which can limit the available power and energy storage capacity. Overcoming these limitations and developing efficient power systems is essential to extend the robot's operational time and capabilities.

However, innovative solutions have been implemented to overcome these challenges. One approach to address power limitations is the use of multiple DC motors instead of a single motor. By employing three DC motors strategically, the robot gains enhanced power and torque capabilities, allowing it to navigate through pipes with varying diameters and surface conditions more effectively.

In addition to power limitations, energy constraints have been tackled by designing in-pipe robots to operate using a wired connection. Although this approach may limit the robot's range of movement compared to wireless alternatives, it ensures a continuous and reliable power supply throughout the robot's operation. By being wired, the robot can overcome energy limitations, enabling extended working periods without the need for frequent recharging or battery replacement.

Furthermore, the weight of the in-pipe robot plays a crucial role in its overall performance. Keeping the robot's weight under 3 kg ensures that it remains lightweight and maneuverable within the pipe environment. This lightweight design enhances the robot's agility and reduces the strain on its motors, contributing to improved energy efficiency and prolonged operation.

These innovative solutions for power and energy limitations demonstrate the continuous efforts to optimize in-pipe robots for enhanced performance. By leveraging multiple DC motors, implementing a wired connection, and maintaining a lightweight design, in-pipe robots can overcome power and energy constraints. These advancements contribute to the robot's ability to navigate through various pipe configurations efficiently, perform tasks effectively, and ensure reliable operation throughout inspection and maintenance operations.

4 Pipe defects

In-pipe defects can pose significant challenges to the integrity and functionality of pipe systems. These defects encompass a range of issues that can compromise the structural strength, fluid flow efficiency, and safety of pipes.

4.1 Corrosion

One common defect is corrosion, which occurs when pipes are exposed to corrosive materials or environmental conditions over time. It can occur due to exposure to corrosive materials, environmental factors, or the age of the pipe. Corrosion is a common and significant problem in various industries, including water distribution, oil and gas, chemical processing, and infrastructure. Different types of corrosion, such as uniform corrosion, pitting corrosion, or stress corrosion cracking, can affect pipe integrity.

4.1.1 Uniform corrosion

Uniform corrosion(Fig. 6(a)) occurs evenly across the entire surface of the pipe. It happens when the metal reacts with the environment, leading to a gradual loss of material thickness. Uniform corrosion tends to happen in mild environments or when the metal is exposed to low levels of corrosive substances.

4.1.2 Pitting corrosion

Pitting corrosion(Fig. 6(b)) refers to localized corrosion characterized by the formation of small pits or holes on the pipe's surface. These pits can penetrate deeply into the metal, causing significant damage. Pitting corrosion often occurs in areas where protective films break down or when localized concentrations of corrosive substances are present.

4.1.3 Crevice corrosion

This type of corrosion(Fig. 6(c)) occurs in confined spaces or crevices on the pipe's surface. These areas can form between pipe joints, under deposits, or due to improper sealing. Lack of oxygen, stagnant fluids, and concentration of corrosive agents within the crevices contribute to accelerated corrosion in these localized areas.

4.1.4 Galvanic corrosion

Galvanic corrosion(Fig. 6(d)) occurs when two different metals or alloys come into electrical contact while being exposed to an electrolyte (e.g., water or moist soil). The more reactive metal, known as the anode, corrodes faster, while the less reactive metal, known as the cathode, experiences less corrosion. Galvanic corrosion often occurs when dissimilar metals are connected through fittings or when pipes are in contact with other metallic structures.

4.1.5 Stress corrosion cracking

Stress corrosion cracking (SCC)(Fig. 6(e)) is a phenomenon where the combined action of tensile stress and a corrosive environment leads to cracks in the pipe material. SCC can occur in susceptible metals or alloys when exposed to specific corrosive agents, such as chlorides, while under sustained stress levels. It can result in rapid crack propagation and catastrophic failure of the pipe.

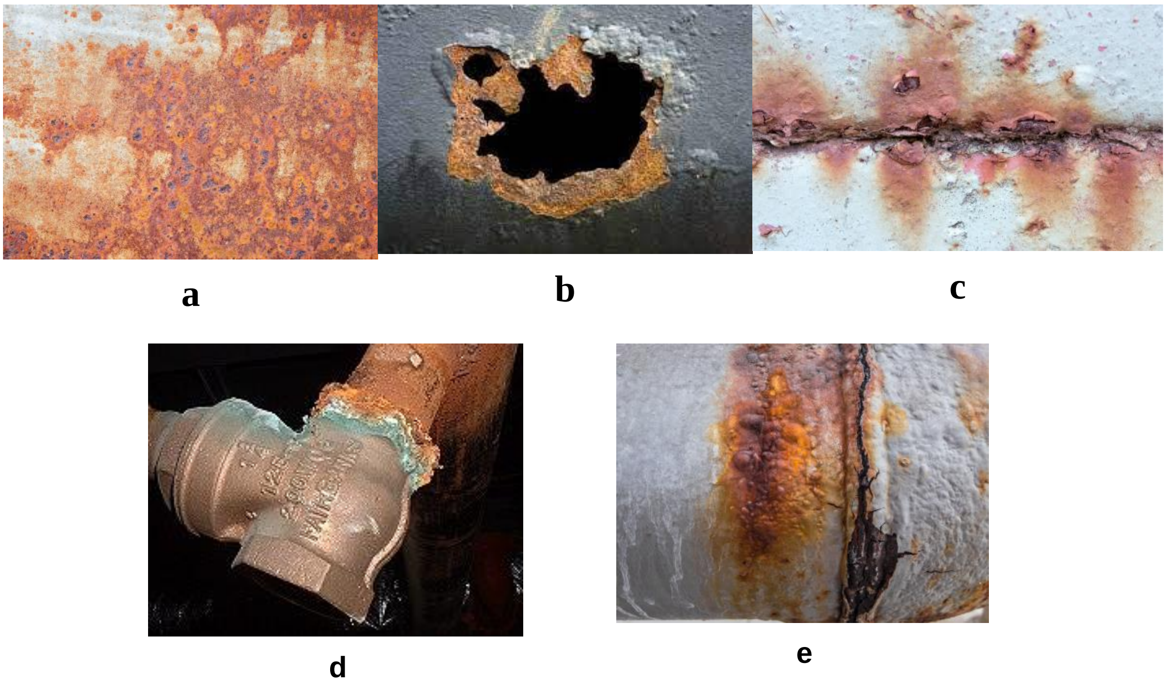

Figure 4.1 – Uniform(1), Pitting(2), Crevice(3), Galvanic(4), Stress(5) corrosions.

4.2 Cracks

Pipe cracks refer to the presence of fissures, fractures, or breaks in the pipe material. These cracks can occur due to various factors such as mechanical stress, fatigue, manufacturing defects, or external forces. Pipe cracks are a significant concern as they can compromise the structural integrity and functionality of the pipe, leading to leaks, reduced flow capacity, or even complete pipe failure.

Pipe cracks can result from different causes. Mechanical stress from external loads, pressure fluctuations, or ground movement can lead to the development of cracks over time. Fatigue, which occurs due to repetitive cyclic loading, can also contribute to crack initiation and propagation. Additionally, manufacturing defects, such as improper welding or material inconsistencies, can create weak points in the pipe susceptible to cracking.

4.2.1 Crack types

Pipe cracks can exhibit different characteristics depending on their formation and behavior. Longitudinal cracks occur parallel to the pipe's axis, while transverse cracks run perpendicular to the axis. Cracks can be surface-level or extend through the entire pipe wall, affecting its structural integrity. Also, they can be single, isolated cracks, or they can occur as multiple interconnected cracks, leading to more complex damage patterns.

4.2.2 Consequences of cracks

Pipe cracks can have detrimental consequences. They can result in leaks, leading to fluid loss, increased operational costs, and potential environmental damage. Cracks can also compromise the pipe's structural strength, increasing the risk of catastrophic failure, which can result in property damage, interruption of services, or safety hazards

4.2.3 Detection and Repair

Early detection of pipe cracks is crucial for timely intervention and preventing further damage. Non-destructive testing techniques, such as visual inspection, ultrasonic testing, or magnetic particle inspection, can be employed to identify cracks. Depending on the severity and location of the cracks, repair methods can include weld repairs, epoxy coatings, pipe clamps, or, in severe cases, pipe replacement.

4.3 Erosion and Abrasion

Pipes conveying abrasive or high-velocity fluids may experience erosion or abrasion. These defects occur when the pipe's inner surface is gradually worn away, leading to thinning of the pipe wall. Erosion and abrasion(Fig 7.) can weaken the pipe and increase the risk of failure.

Figure 4.3 – Abrasion of inner wall of pipe

4.4 Deformation

Pipe deformation refers to changes in the shape or geometry of a pipe that deviate from its original or intended form. Pipe deformation can negatively impact the performance, structural integrity, and fluid flow characteristics of the pipe.

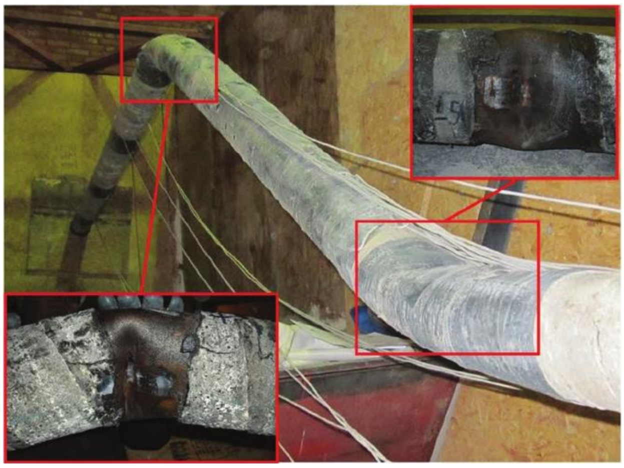

Figure 4.4 – Pipe deformation

It can result from different causes. External forces, such as heavy loads, ground movement, or impact, can lead to bending, buckling, or other forms of deformation. Temperature variations, thermal expansion, and contraction can cause the pipe to expand or contract, resulting in changes in shape. Manufacturing defects, such as improper shaping or inadequate material quality, can also contribute to deformation.

Pipe deformation can have several negative consequences. It can affect the pipe's load-bearing capacity, leading to reduced structural strength and increased vulnerability to failure. Deformation can also impact the pipe's hydraulic performance by altering its flow capacity, causing flow restrictions, increased pressure losses, or flow turbulence. In severe cases, deformation can result in pipe leakage, system inefficiency, or even complete pipe rupture.

Corrosion of pipes is a common issue that can lead to the degradation and failure of the pipe material over time. It occurs when the pipe material reacts with its surrounding environment, resulting in the loss of material and deterioration of the pipe's structural integrity. Corrosion can be influenced by various factors, including the type of material used for the pipe, the nature of the environment, and the presence of corrosive agents.

Table 4 – Comparing table of different types of corrosion

Corrosion Type	**Description**	**Appearance**	**Causes**	**Factors**
Uniform	Occurs evenly across the entire surface of a material	Generalized loss of material	Chemical reactions between the metal and the environment	Exposure to corrosive agents, temperature, humidity, pH level
Pitting	Forms localized pits or cavities on the metal surface	Small, localized holes or craters	Irregularities in the metal surface or localized breakdown of passivation	Presence of aggressive ions, stagnant conditions, oxygen concentration cells
Crevice	Occurs in crevices or gaps between two surfaces	Corrosion localized in narrow gaps or crevices	Differential aeration cells and restricted access to oxygen	Presence of stagnant electrolyte, crevice geometry, temperature
Galvanic	Results from the coupling of two dissimilar metals in an electrolyte	Attack occurs on the less noble (more reactive) metal	Electrochemical reactions due to the galvanic couple	Dissimilar metals, electrical conductivity, electrolyte conductivity
Stress	Occurs in the presence of tensile stress and a corrosive environment	Cracking or corrosion under stress	Combined effect of stress and corrosive environment	Stress level, environment composition, material susceptibility

5 Diagnostics of pipe

In-pipe diagnostics refer to the methods and techniques used to assess the condition and performance of pipes from within, enabling the detection of defects, blockages, leaks, or other issues. These diagnostics methods are essential for identifying potential problems, conducting maintenance, and ensuring the reliable operation of pipe systems.

5.1 Visual inspection

Visual inspection(Fig 9.) involves directly examining the interior of pipes using specialized cameras or inspection tools. It provides a visual assessment of the pipe's condition, identifying cracks, corrosion, deformations, blockages, or other visible defects. Visual inspection can be performed using robotic cameras, endoscopes, or remotely operated vehicles (ROVs).

Figure 5.1 – Visual inspection

5.2 Ultrasonic testing

Ultrasonic testing(UT)(Fig 10.) utilizes high-frequency sound waves to detect and evaluate the thickness, integrity, and presence of defects within the pipe. UT sends ultrasonic waves into the pipe material, and the reflections or echoes are analyzed to determine wall thickness, corrosion levels, or the presence of cracks or flaws. This method is commonly used for assessing metal pipes. Ultrasonic testing works based on the principle of sound wave propagation. A transducer emits ultrasonic waves into the material being tested, and these waves travel through the material until they encounter a boundary or defect. When the waves hit a boundary or defect, they are reflected back to the transducer. By analyzing the time taken for the waves to travel and the characteristics of the reflected waves, important information about the material and any flaws can be obtained.

Figure 5.2 – Ultrasonic testing

UT can be performed using various techniques, depending on the specific requirements and characteristics of the material being tested. The two primary techniques are pulse-echo and through-transmission. In pulse-echo testing, a single transducer both emits and receives the ultrasonic waves. In through-transmission testing, two transducers are used, with one emitting the waves and the other receiving them on the opposite side of the material.

5.3 Magnetic Flux Leakage(MFL)

MFL is a non-destructive testing technique used primarily for inspecting metallic pipes. It involves passing a magnetic field through the pipe, and any changes in the magnetic field caused by defects, such as corrosion or wall loss, are detected and analyzed. MFL is effective in detecting localized or general corrosion, pitting, and wall thinning.

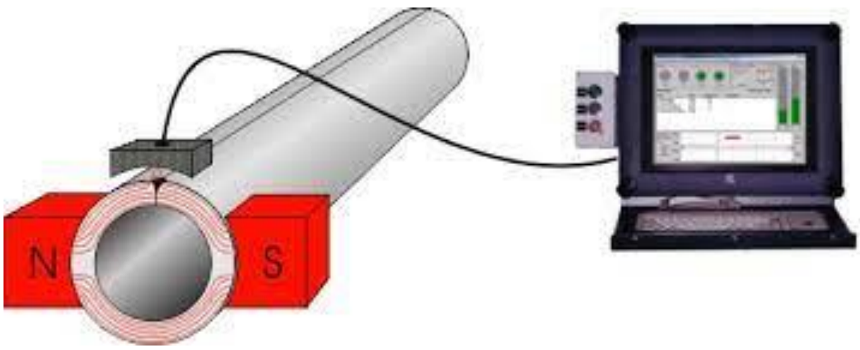

Figure 5.3 – Magnetic Flux Leakage

5.4 Pipe Pressure Testing

Pressure testing involves subjecting the pipe to higher than normal operating pressures to assess its integrity. By monitoring pressure levels and observing pressure drops over time, leaks, cracks, or weak spots in the pipe can be identified. This method is commonly used during pipe installation or after repairs.

Figure 5.4 – Pipe Pressure Testing

5.5. Chemical testing

Chemical testing involves collecting and analyzing samples of fluid or material from within the pipe to assess its composition, corrosion levels, or the presence of contaminants. It can help identify the type of corrosion, assess water quality, or detect the presence of chemicals that may contribute to pipe degradation. A manipulator can be installed on the rear end of an in-pipe robot to retrieve samples from within the pipes to facilitate further analysis of them.

In the field of pipe diagnostics, various methods are used to assess the condition of pipes. Visual inspection is a non-destructive and cost-effective method that allows for direct examination of the pipe surface. Ultrasonic testing (UT) provides high accuracy and can detect internal and external defects. Magnetic Flux Leakage (MFL) is a sensitive method for detecting corrosion and defects, but it is limited to ferromagnetic materials. Pipe pressure testing is a valuable method for detecting leaks and weaknesses, although it is a destructive approach that requires shutting down the system. Chemical testing can identify corrosive elements and determine the corrosion rate, but it is primarily focused on chemical corrosion.

It's important to note that selecting the appropriate diagnostic method depends on specific requirements, pipe accessibility, and the type of defects or corrosion being targeted. Combining multiple methods can provide a more comprehensive assessment of pipe condition. Each method has its advantages and limitations, and the choice of method should be made based on the specific needs and constraints of the pipe diagnostics application.

Table 5 – Comparing table diagnostic methods used for pipes

Diagnostic Method	Description	Advantages	Limitations
Visual Inspection	Direct visual examination of the pipe surface	Non-destructive, low cost	Limited to external surface inspection, may not detect internal defects
Ultrasonic Testing (UT)	Uses high-frequency sound waves to detect defects	Can detect internal and external defects, high accuracy	Requires trained operators, limited to accessible areas
Magnetic Flux Leakage (MFL)	Uses magnetic fields to detect corrosion and defects	Can detect internal and external defects, high sensitivity	Limited to ferromagnetic materials, complex data interpretation
Pipe Pressure Testing	Applies pressure to the pipe to check for leaks or integrity	Can detect leaks and weaknesses	Destructive method, requires shutting down the system
Chemical Testing	Analyzes the composition of fluids or deposits in the pipe	Identifies corrosive elements, can determine corrosion	Limited to detecting chemical corrosion, not suitable for detecting physical defects

6 System Architecture

6.1.1 Sensor Acquisition and Integration

In-pipe diagnostics play a vital role in assessing the condition and integrity of pipes, ensuring their reliable operation and minimizing the risk of failures. One advanced approach in this field is the utilization of Time-of-Flight (TOF) sensors, which provide valuable data for comprehensive analysis. This paragraph will focus on the integration of a TOF sensor within an in-pipe robot, enabling the collection of distance measurements between the robot's center and the pipe wall.

To enhance the diagnostic capabilities, a TOF sensor is mounted on a servo mechanism, allowing it to rotate 360 degrees both forward and backward. This setup enables the sensor to capture distance readings from various angles around the robot's center. The servo mechanism is centrally mounted on the in-pipe robot, ensuring that measurements are taken consistently from the pipe's interior.

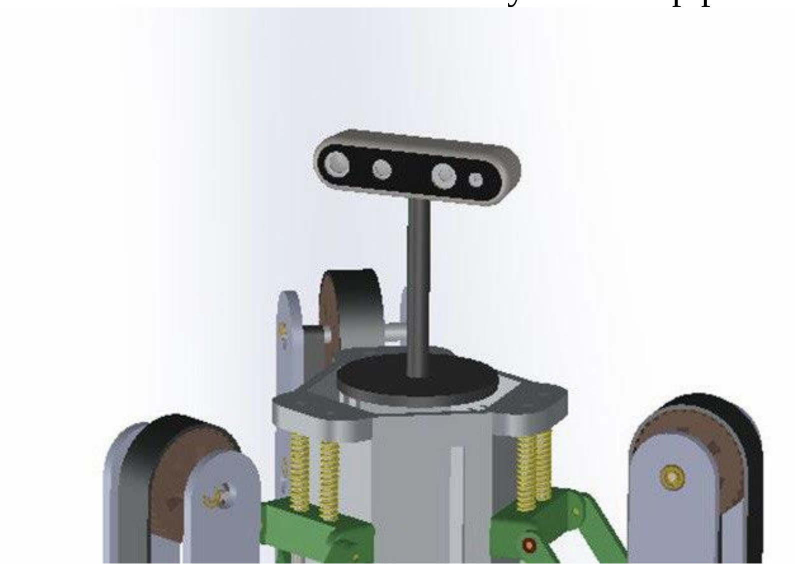

Figure 6.1.1 – TOF sensor mounted on the robot

As the robot moves through the pipe, the TOF sensor continuously collects distance data between the robot's center and the pipe wall. This data is then processed and stored in a database, facilitating further analyses. To enable real-time monitoring and visualization of the collected information, the database is transmitted to a Python program via a communication port.

In Python, the received data is utilized to generate polar graphs that accurately depict the shape of the pipe. These polar graphs provide valuable insights into the pipe's condition, allowing for the identification of irregularities, deformations, or potential issues along its length. The Python program utilizes the PyQt5 library to create an interactive interface, where the plotted pictures of the pipe's shape are displayed for further analysis and examination.

6.1.2 Alert System of Application

Implemented alert system that triggers when certain predefined conditions are met. For example, if the distance between the robot and the pipe wall less than a specified threshold or if a sudden change in signal strength occurs, the interface can display a visual alert to draw attention to potential issues.

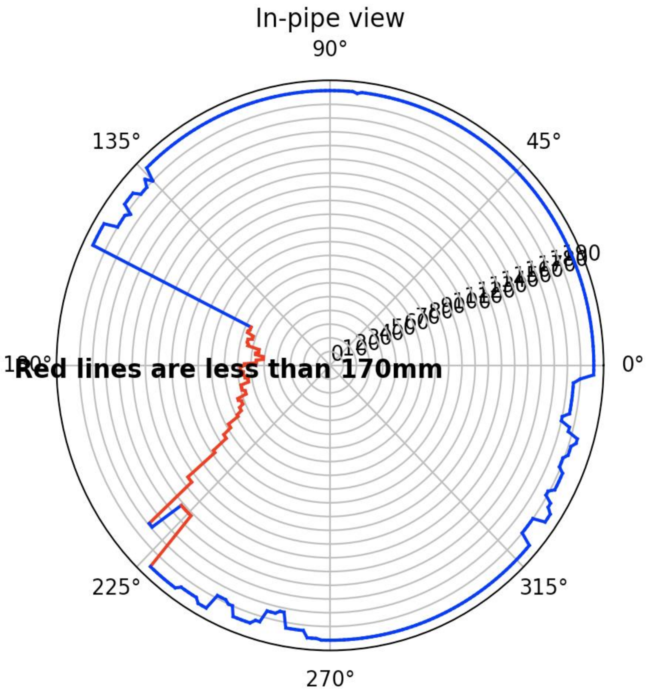

Figure 6.1.2 – Graph depicts the shape of the pipe

This integration of a TOF sensor with a rotating servo mechanism on an in-pipe robot, coupled with the data collection, database creation, and Python-based analysis, offers an advanced and efficient solution for in-pipe diagnostics. The ability to visualize the pipe's shape through polar graphs in real-time provides valuable information for maintenance planning, defect detection, and decision-making in the context of pipe infrastructure management

6.2.1 Light Detection and Ranging(LIDAR) camera as a diagnostics tool

Lidar is a remote sensing technology that uses laser light to measure distances and generate detailed 3D maps or point clouds of the surrounding environment. It works on the principle of emitting laser pulses and measuring the time it takes for the pulses to bounce back after hitting objects in the environment. Lidar systems typically consist of a laser source, scanner or rotating mirror, photodetector, and associated electronics.

Lidar devices, such as the Intel RealSense depth camera, can capture depth information for each point in the scene. This enables accurate measurements of distances to objects, allowing the creation of detailed 3D models of the pipe or the surrounding environment.

Figure 6.2.1 – Intel realsense camera

It scans the environment by emitting laser pulses and measuring the reflected light. By combining these measurements, a point cloud is created, which represents a collection of 3D points in space. Each point in the point cloud contains spatial coordinates (x, y, z) and additional information such as intensity or color.

The study investigates the integration of Intel RealSense Depth Camera (LIDAR) technology within a pipe robot system to facilitate the diagnosis of pipe conditions. By employing LIDAR technology in conjunction with Time-of-Flight (TOF) sensors, a comprehensive 3D representation of the pipes can be generated. This enables precise capture of the pipes' shape, size, and position by scanning them from multiple viewpoints. The acquired information holds significant potential for a range of applications, including visualizing the pipe network, identifying anomalies or damages, and evaluating the overall condition of the pipes.

6.2.2 Soft to develop 3d processing

Python provides a variety of libraries and frameworks that are suitable for handling Lidar data. Open3D, PyntCloud, and PDAL are among the well-known options. These libraries offer a range of capabilities for manipulating, filtering, segmenting, registering, and visualizing point clouds. Utilizing these resources, one can process the Lidar data, refine it, extract pertinent features, and conduct comprehensive analysis of the pipe conditions.

After obtaining the 3D model and processed Lidar data, several assessments can be carried out to evaluate the pipe's condition. This entails the identification of cracks, corrosion, leaks, blockages, and other irregularities in the pipe structure.

7 Robot’s fit in the pipe

Various types of connections can be employed to enhance the force exerted between the robot's driving "legs" and the pipe surface. Irrespective of their specific design and type, these connections need to ensure optimal adjustment of the robot to accommodate different variations in pipe diameter. Moreover, they must maintain a consistent and adequate pressure to enable the robot to bear its own weight and move along the pipe. In the case of in-line inspection robots belonging to different categories, the links utilized to adapt the mechanisms essentially dictate their mechanical structure and size. Consequently, the choice of connection and the correct design approach can significantly impact a robot's performance.

7.1 Wheel driven robot

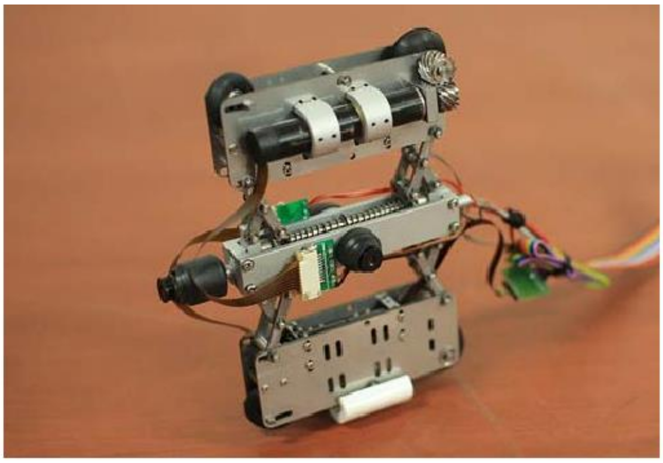

Figure 7.1 – Wheel driven robot

These robots employ wheels that are powered by actuators or gear motors to facilitate their movement. Many wheeled robots incorporate adaptation mechanisms to ensure a consistent grip on the pipe surface, which is particularly crucial when scaling vertical pipes. Another type of robot within this category is a simpler wheel-driven linear robot that is specifically designed for horizontal motion and lacks adaptable arms. Depending on the robot's design parameters, it can feature a two-, three-, or six-wheeled configuration evenly distributed around its central axis. Wheeled robots are characterized by their straightforward design, maneuverability, and efficiency in long-term operations. However, due to the small size of their wheels, they possess a limited contact area with the pipe walls, which can result in the robot becoming stuck on bumps or irregularities inside the pipe.

Kwon et al. [16], proposed a pipeline inspection robot(Fig. 16) designed for inspecting pipelines with a diameter range of 80-100mm. This robot stands out due to its unique ability to achieve both driving and steering functionalities using only two wheel chains. This design innovation simplifies robot control and provides a user-friendly interface, particularly in challenging areas such as T-branch junctions.

Additionally, the robot's flat shape enables the mounting of additional sensors on both sides, offering an added advantage in terms of sensor capabilities and data collection.

7.2 Pipe inspection gauge robot(PIG)

The PIG is a widely utilized type of rugged pipeline inspection robot, primarily employed for pipeline cleaning and condition assessment. It is specifically designed for a particular pipe diameter. The PIG robot is launched into the pipeline and retrieved at a designated station. Its propulsion is achieved either through fluid velocity or magnetic flux. Equipped with multiple sensors, the robot collects various data including its orientation, speed, vibration, temperature, location, and the inside diameter of the pipe. Being a wireless system, the PIG robot incorporates a built-in battery and data storage unit, allowing data to be collected upon retrieval. However, these robots typically lack actuators, which restricts them from executing complex movements.

Figure 7.2– PIG

D. Mishra et al. [17], proposed a groundbreaking autonomous crawler (Fig. 17) designed for pipeline inspection in crude oil environments. This specialized pipe inspection gauge operates by utilizing the kinetic energy generated by the movement of crude oil mixed with a slug inside the deeply buried pipelines. The selection of components in the development of these robots prioritizes intrinsic safety, ensuring the device is safe to use. The primary purpose of this gauge is to assess the health of deeply buried cross-country pipelines that lack their own power source for internal locomotion.

7.3 Walking type robot

Legged or walking robots rely on walking legs with multiple freedom degrees to achieve locomotion. These robots offer the advantage of being able to avoid by stepping over obstacles during travel, making them suitable for applications such as sewer inspection where clearance from water bodies is necessary. Each leg's motion is controlled by numbers of actuators, resulting in a cumbersome system due to the large number of actuators incorporated inside the robot. Designing such robots poses challenges in terms of sequence and trajectory generation, inverse kinematics, system control, and other related aspects. Additionally, the legs of these robots provide a smaller contact area, which can limit their traction capabilities.

In the study conducted by S. Savin et al. [18], simulations were performed on the motion legs of a walking robot. The results revealed that employing an interactive linear state observer had a significant positive impact on the behavior of the control system, particularly in the presence of sensor noise and data quantization. The researchers demonstrated that the incorporation of the state observer enabled the use of higher feedback controller gains when utilizing a computed torque controller.

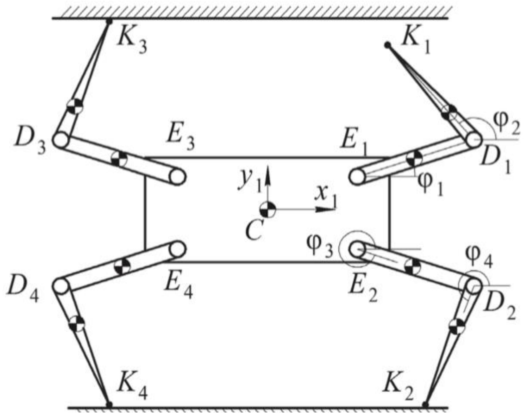

Figure 7.3 – Diagram of the in-pipe walking robot.

However, for the state observer to be used in the full robot mode, it was necessary to incorporate information about reaction forces into the observer design. Remarkably, the robot exhibited commendable performance even when faced with noise and quantization in the reaction forces data.

7.4 Comparison of different types of robots

When comparing the characteristics of different robots mentioned above, steerability becomes an important factor, especially when maneuvering around joints and curves. Steerability is readily achievable in wheel-type, track-type, and legged-type robots. In track-type robots, steerability is attained by employing differential speeds on the track wheels. On the other hand, pig-type robots lack a steering mechanism and are therefore more suitable for straight pipelines. Modules without steering mechanisms are generally preferred for pipelines without curves or turns, such as direct drain lines.

When it comes to accommodating variations in diameter and adapting to different pipe joints, wheel-type and track-type robots are the preferred options among other robot types. These robots typically employ a four-bar linkage mechanism to ensure adaptability and generate traction. In contrast, PIG robots lack a mechanism for adapting to the pipe. On the other hand, screw-type robots are equipped with telescopic suspension, which enables them to adjust their height and length and to adapt to variations in the pipe diameter by extending or retracting the suspension mechanism to fit different pipe sizes.

Table 7 − Comparing table of different types of in-pipe robots

In-Pipe Robot Type	Description	Advantages	Limitations
Wheel-Driven Robot	Uses wheels or tracks to move through the pipe	Fast and efficient movement, suitable for straight pipes	Limited maneuverability in curved or complex pipe networks
Pipe Inspection Gauge Robot (PIG)	Designed for pipeline inspection, typically propelled by fluid flow	Can traverse long distances, collects data during inspection	Limited control over movement, mainly suitable for liquid-filled pipelines
Walking-Type Robot	Utilizes legs or walking mechanisms for locomotion	Versatile movement in various pipe configurations, can navigate obstacles	Slower speed compared to wheel-driven robots, complex design and control mechanisms

Each diagnostic method has its own advantages and limitations, and the choice of method depends on the specific requirements, accessibility, and nature of the pipe being tested.

7.5 Pipe adaptivity of robot

Each drive is equipped with a single geared motor, and the robot's locomotion within the pipe relies on one drive motor per leg. The torque generated by the drive motor is transferred to the drive wheels via pulleys and a belt. Although this arrangement adds complexity to the motion control system, it enhances the traction force and improves the robot's ability to adapt, particularly when navigating curved and twisting pipes. Since each "leg" has an individual speed and direction of rotation independent of each other.

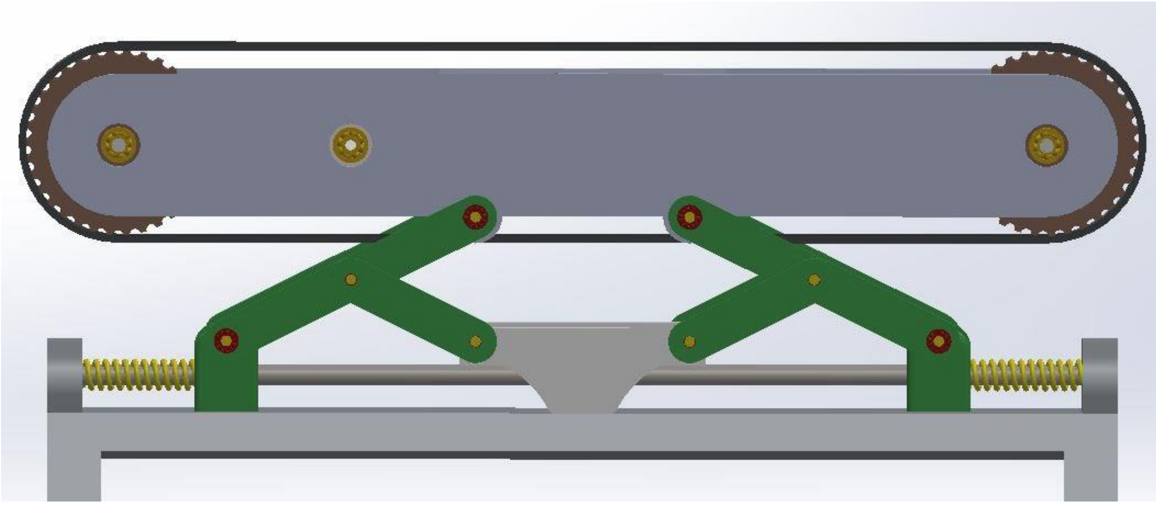

Figure 7.5 – Active passive(slider)

The robot has active and passive modules that are connected to bearings and shafts, allowing the robot's legs to move flexibly. Active modules - sliders driven by springs and moving along a shaft with a linear bearing.These modules serve as a support system for the robot. They rely on a spring that exerts pressure on the slider, creating a pressing force against the pipe wall. This mechanism allows the robot to adapt to various pipe diameters by expanding or contracting the slider linkage in response to the force exerted by the spring. The spring's force compensates for any changes in the friction between the wheels and the pipe wall, ensuring consistent traction and adaptation of the robot to different pipe sizes.

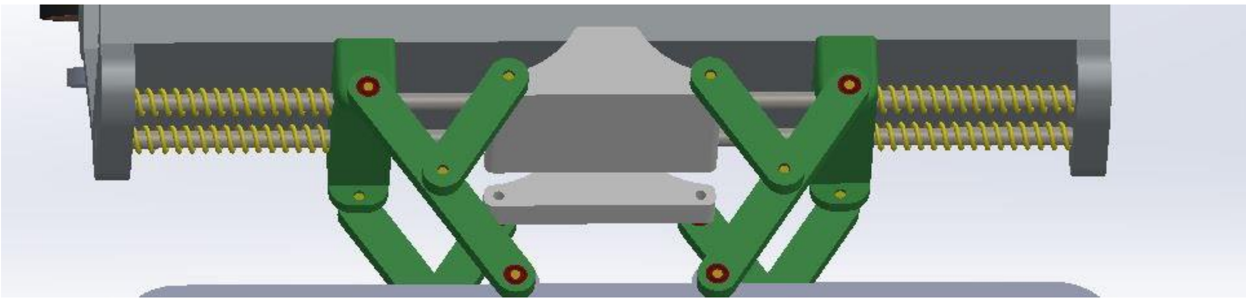

Figure 7.5.1 – Adapting mechanism(springs)

The primary role of the mobile unit is to supply the necessary traction for propelling the entire robot through the pipe. Figure 5 depicts the schematic diagram of the adapting mechanism designed for one of the three drive wheels. **Spring** loaded caterpillar wheels provide shape adaptability and enhance friction between robot and pipe interior. Due to its flexibility motor can transmit torque to rotor even in case of minor misalignments and can easily be stopped at any point of journey inside the vertical or horizontal pipeline. Springs enable the legs of the robot to change with the environment and achieve stable operation of the robot under a larger range of pipe diameter values and under a larger weight load.

8 Configuration of The Robot

In general, the robot includes a central part that houses a control module, driving parts, a cable for control and power, and optional instrument modules like a camera and an optical sensor for non-destructive testing.

Figure 21 displays a potential configuration of the robot, where the different modules are functionally separated. These modules include drive modules, control modules, and non-destructive testing modules. The primary design objective of the robot is to have sufficient traction to ascend vertical pipelines and pull the cables that provide power to the robot. Each "leg" of the robot features flexible caterpillar supports that press against the pipeline's inner wall, utilizing friction to generate driving forces. As the robot moves forward, the DC motors in the legs create a pulling force, while the springs in the central block generate a pushing force for the legs. Other passive modules, such as the connections between the central part and the legs, utilize bearings and shafts.

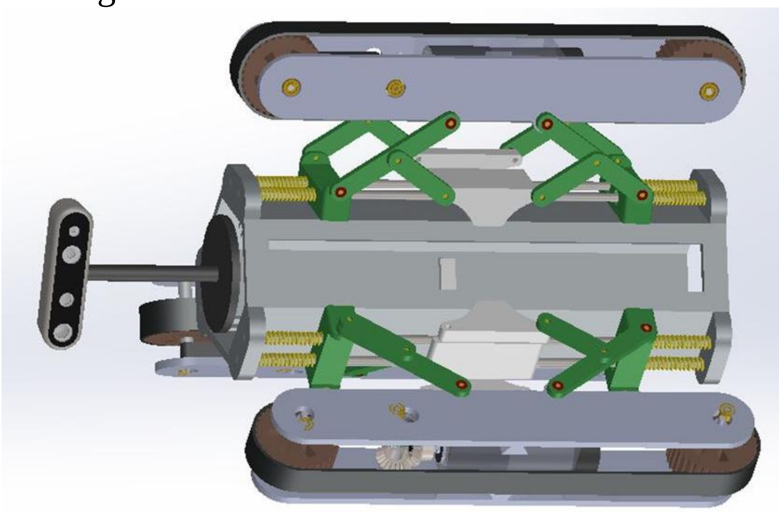

Figure 8 – Assembled robot

To communicate with the joystick and the computer, the in-line robot uses a cable. This tethered cable consists of power lines, optical fibers for video signals, and digital data transmission.

8.1 Detailed description of the main technical characteristics of the robot

Weight: 3-4kg(approximately);

Dimensions: 300x290mm expanded(approx), 290x190x190mm compressed

Frame materials: PLA, FLEX plastics, steel, aluminum

Robot system components: Depth camera, TOF sensor, Controller based on Atmega processor, Position sensors, DC motors at 12Volts, Dotor drivers, Servo, DC-DC converters, Circuit board, Backlight LEDs, 2 toothed pulley(2-GT-3.6mm diameter bore), 3D printed FLEX timing belt, pulley belt(2-GT, 63MXL), Bearings(with inner hole diameter 3mm and outer diameter 10mm), Shafts with a diameter of 3mm, 10-pin plug-in terminal block.

8.2 Circuit diagram

The circuit diagram of the in-pipe robot includes a compactly designed board mounted on the center module of the robot. This board houses various components that are essential for the robot's functionality. At the core of the circuit is the Arduino Nano, which serves as the main controller for the robot. It provides the necessary processing power and interfaces with other components to control the robot's movements and functions.

To control the DC motors responsible for the robot's movement inside the pipe, a DC motor driver module called DRV8833 is utilized. This motor driver allows the Arduino Nano to regulate the speed and direction of the motors effectively. Power supply management is addressed by a DC-DC converter, which converts the higher voltage (12V) available in the robot's power source to a lower voltage (5V) required by the Arduino Nano and the motor driver. This converter ensures stable and regulated power supply to these components.

To facilitate easy integration and replacement of sensors and other parts, interface chips are employed on the board. These chips provide convenient means to disable or replace sensors and parts without requiring extensive rewiring or modifications. Additionally, resistors are strategically placed on the board to perform various functions such as current limiting, voltage division, and pull-up/pull-down configurations. These resistors play a critical role in ensuring proper circuit operation and protecting the components.

Overall, the design of the board and the circuit aims for compactness, allowing it to fit within the limited space available in the in-pipe robot. This compact design optimizes the utilization of space while ensuring that all necessary components are integrated and properly connected, enabling efficient control and operation of the in-pipe robot.

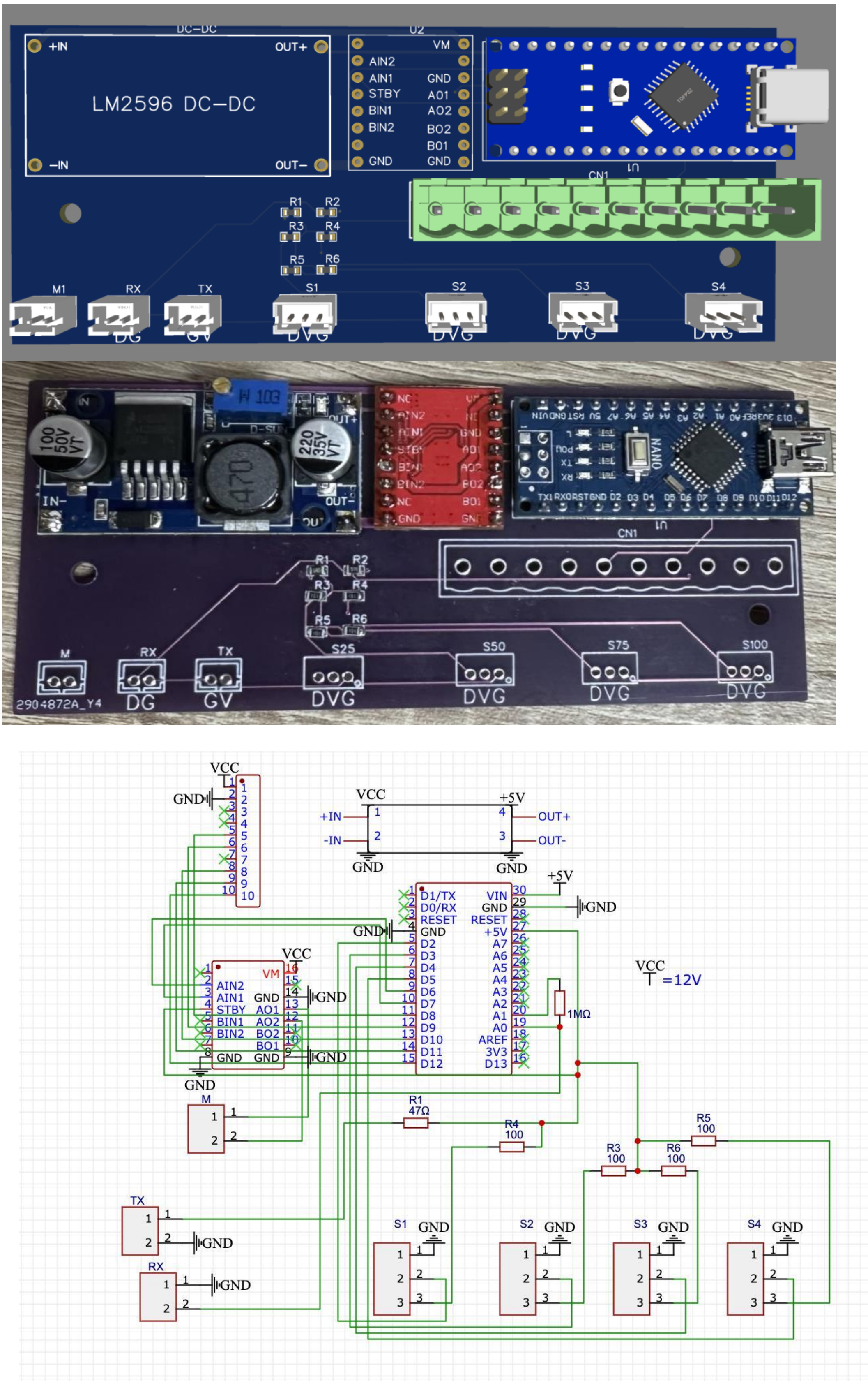

Figure 8.2 – Circuit diagram and board

8.3 Speedometer from Hall effect sensor

The Hall effect sensor operates based on the principle of the Hall effect, which states that when an electric current flows through a conductor and a magnetic field is applied perpendicular to the current, it induces a potential difference. This voltage change can be utilized to detect the presence or absence of a magnet near the sensor. The Arduino microcontroller is capable of sensing this voltage variation through its interrupt pin, enabling it to determine the proximity of the magnet to the sensor. The diagram below illustrates the fundamental functioning of the Arduino Hall effect sensor.

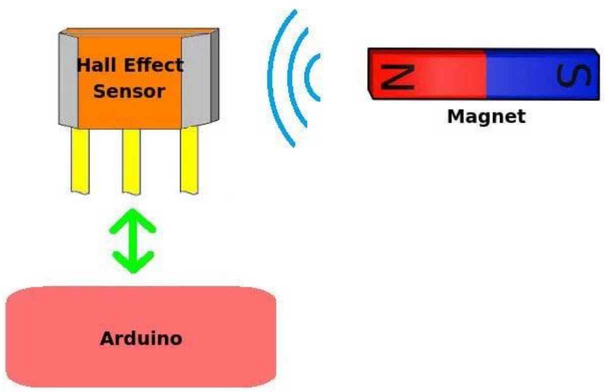

Figure 8.3.1 – Arduino Hall effect sensor

Hall effect sensors come in various types, each suitable for different applications. For high-speed detection applications like speedometers, it is recommended to use high-frequency Hall effect sensors such as the US5881 or US1881. There are two main categories of Hall effect sensors: latching and non-latching.

The US1881 is an example of a latching Hall effect sensor. When a magnet's north pole is brought close to the sensor, it outputs a HIGH (5V) voltage. Even after removing the magnet, the sensor continues to output a HIGH voltage until a south pole magnet is brought near it. These sensors maintain their state and are known as latched Hall effect sensors.

In contrast, the US5881 is a non-latching Hall effect sensor. It produces a HIGH voltage when a magnet's north pole approaches the sensor and switches to LOW when the magnet is removed. Personally, I prefer using non-latching Hall effect sensors like the US5881 for my projects. Hall effect sensors typically have three pins: VCC (5V), GND, and Vout (Signal).

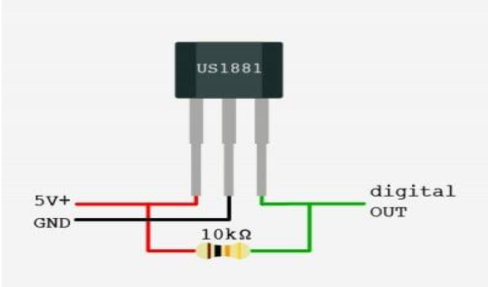

Figure 8.3.2 The pinout diagram for a Hall effect sensor

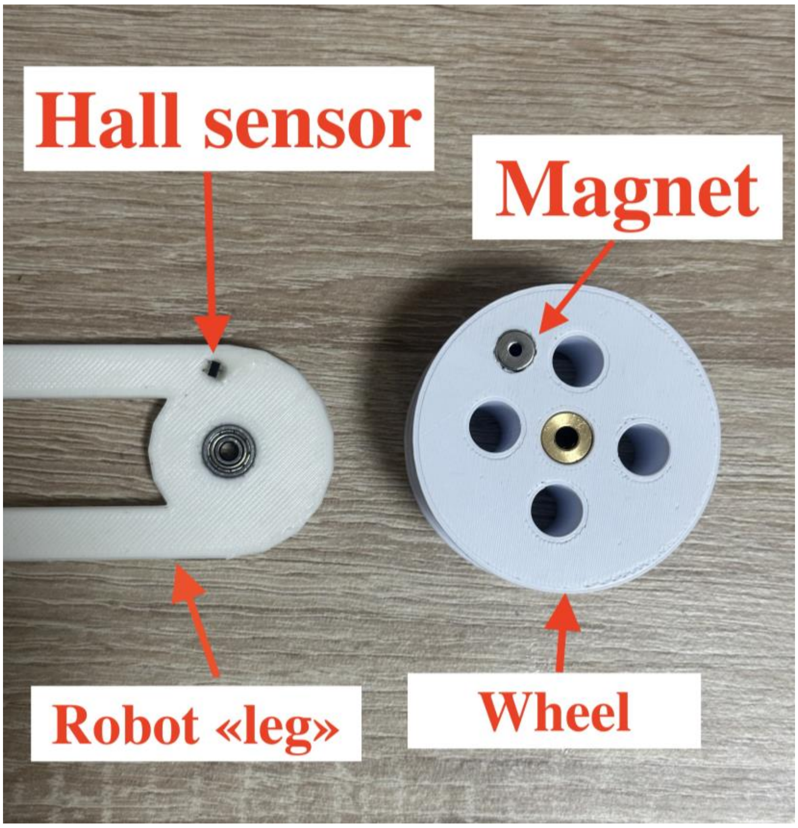

Figure 8.3.3 – Installing the sensor and magnet

In a Hall sensor-based odometer, a Hall sensor is typically used to detect the rotation of a magnetic wheel or a gear attached to the wheel. The Hall sensor generates electrical pulses as the magnetic field changes, and these pulses are counted to determine the distance traveled.

The formula to calculate distance or displacement using a Hall sensor-based odometer can be derived as follows:

$$d = P \times c, \tag{9.1}$$

where d – distance travelled, m;

P – pulses per revolution, pulses;

c – circumference of wheel, m.

$$c = 2\pi \times r, \tag{9.2}$$

where r – radius of wheel, m.

$$v = \frac{d}{t}, \tag{9.3}$$

where v – velocity, m/s;

t – time taken to cover the distance, s.

To interface the Hall effect sensor with an Arduino, needed to connect the sensor's pins to specific pins on the Arduino board. Here's the connection setup:

- VCC (5V) pin of the Hall effect sensor to the 5V power pin on the Arduino.
- GND pin of the Hall effect sensor to the GND pin on the Arduino.
- Vout (Signal) pin of the Hall effect sensor to the Arduino's interrupt pin. It is connected to digital pin 2 on the Arduino.

Additionally, included a 10K resistor in the circuit. One end of the resistor is connected to the VCC pin of the Hall effect sensor, and the other end to the Vout pin of the sensor. This resistor is used as a pull-up resistor to ensure that the output of the Hall effect sensor is pulled to a HIGH (5V) state when no magnet is present.

The code provided implements a mechanism for measuring the speed of a rotating wheel using a Hall sensor. The Hall sensor, connected to digital pin 2 of the Arduino board, detects triggers as the wheel rotates. These triggers are generated by markers mounted on the wheel and passing by the sensor.

The **hallInterrupt()** function serves as an interrupt service routine, triggered whenever a falling edge is detected by the Hall sensor. Each trigger increments the **triggerCount** variable, allowing the system to keep track of the number of triggers observed.

During the setup phase, the pin mode of the Hall sensor pin is set to **INPUT_PULLUP**, enabling the internal pull-up resistor on the Arduino board. This configuration ensures that the default state of the Hall sensor pin is HIGH. Additionally, the **attachInterrupt()** function associates the **hallInterrupt()** function with the interrupt generated by the falling edge on the Hall sensor pin.

Within the main loop, the system measures the speed of the wheel at regular intervals. The time elapsed since the previous speed calculation is obtained using the

millis() function. If this elapsed time exceeds a predefined interval (**speedInterval**), the interrupt is temporarily disabled to prevent further trigger counting.

The distance traveled by the wheel is then calculated by multiplying the circumference of the wheel with the number of triggers counted. Subsequently, the speed is determined by dividing the distance by the elapsed time.

After the speed calculation, the **triggerCount** is reset to zero, and the interrupt is reattached to resume counting triggers. The calculated speed value is printed to the serial monitor using the **Serial.print()** and **Serial.println()** functions.

In summary, the implemented code continuously monitors the Hall sensor triggers and calculates the distance traveled by the wheel. This information, along with the elapsed time, enables the determination of the wheel's speed in meters per second. The recorded speed values are displayed on the serial monitor for further analysis and troubleshooting.

8.4 3D printed caterpillar belt

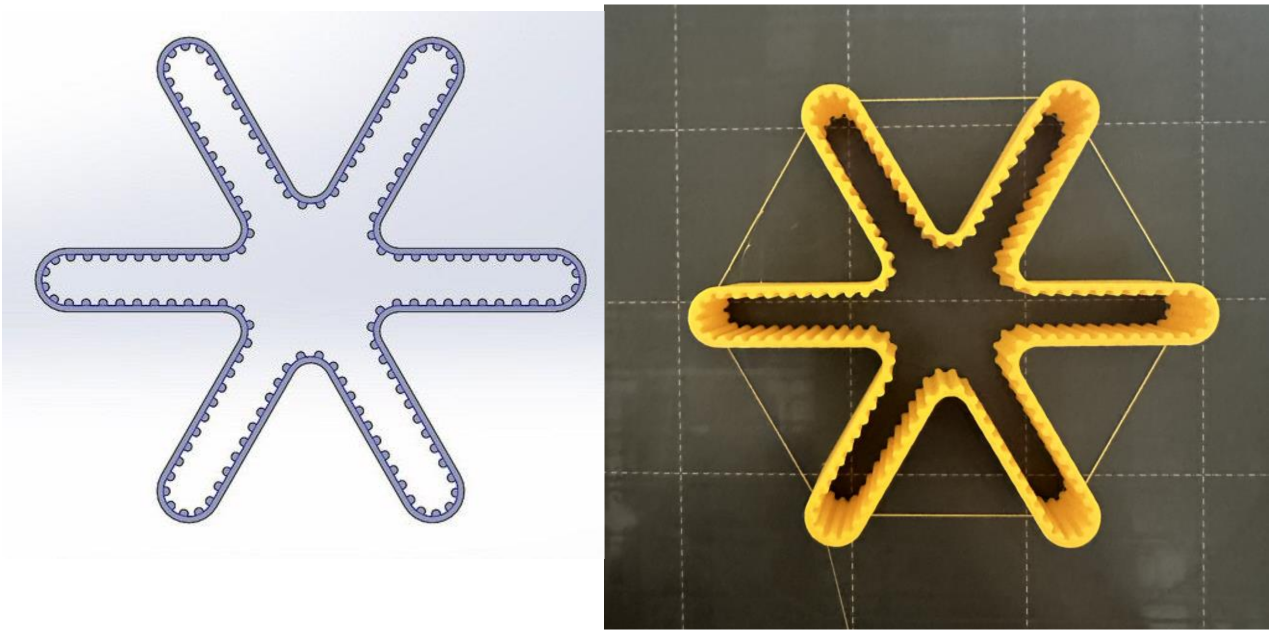

Figure 8.4– 3D and printed versions of belt

In order to fit desired size of legs belts are printed from FLEX material. FLEX is a collective term used to describe a group of plastics used in FDM (Fused Deposition Modeling) printing. The defining characteristic of these plastics is their flexibility, stretchability, and rubber-like nature, making them elastic. As a result, they are commonly referred to as elastomers. Typically, FLEX plastics are composed of polyurethane, rubber, or various combinations of these materials in different proportions. Additionally, they may contain dyes and other additives that enhance their properties and facilitate the 3D printing process.

The hexagonal shape of the print was chosen for more accurate printing of the model, since if you print one large circle, then layer by layer the part will lose its original shape.

Printing on flexible materials involves using specialized printing methods and equipment designed to accommodate the material's flexibility and stretchability. Various techniques are available for printing on flex materials, including screen printing, heat transfer printing, direct-to-fabric printing, and flexographic printing. These methods enable vibrant and durable prints on flexible surfaces. Factors such as the material's stretchability and surface texture should be considered when choosing the appropriate printing technique. Consulting with printing professionals can provide valuable guidance on selecting the best printing method and materials for specific applications.

Building an autonomous robot is the final step in assembling all components, bringing together mechanical, electronic, and software elements to create a functional unit capable of operating in various specific conditions. Integrating all the components ensures their interaction and eliminates potential inconsistencies, enabling the system to perform its intended tasks efficiently and effectively.

Figure 8.4.1 The assembled In-pipe robot v1.0.

To ensure successful integration, the following aspects need to be considered:

- Mechanical integration: This involves assembling the mechanical components of the robot, such as the body, chassis, joints, and other mechanisms, to ensure the stability, reliability, and freedom of movement within the pipeline. Proper assembly and technical compatibility are crucial for optimal performance and operational efficiency.

- Electronic integration: Electronic components, including control boards, sensors, actuators, and other electronic devices, must be correctly interconnected and integrated into the system. This includes proper placement, installation of connections, verification of electrical compatibility, and ensuring the reliable functioning of all components.

- Software integration: Various software modules and control algorithms need to be integrated into a software system. This includes coordinating the functions of different modules, exchanging data between them, handling external events, and facilitating interaction with an operator or external systems.

- Testing and debugging: Testing and debugging are essential stages of the integration process. They involve verifying the system's functionality, identifying and resolving potential errors, and improving the robot's performance. Testing can be performed at both component and system levels, ensuring the rectification of identified issues and enhancing the robot's overall functionality.

- Validation and verification: After integrating all components, the robot's performance needs to be validated and verified. This process ensures that the system meets predefined requirements and objectives. Validation allows for the execution of predefined tasks, identification of deviations, and improvement of the robot's functionality. Verification ensures the proper functioning of all system components and modules.

The integration of all components is a critical step in developing an in-pipe mobile robot. It enables the robot to be used in specific pipeline conditions and facilitates system construction. The integration of the in-pipe mobile robot's components involves additional aspects such as:

- Calibration and adjustment: This is an important part of the integration process, which includes calibrating and adjusting all the robot's sensors and devices. It involves identifying and correcting possible errors, drifts, and noise to optimize the system's accuracy.

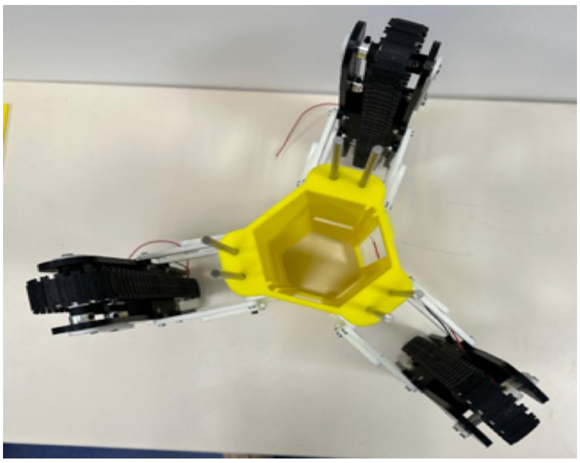

Figure 8.4.2 Top view In-pipe Robot v1.0

- Functional testing: After integrating all the components, it is necessary to test the robot's functionality. This includes evaluating the performance of all operational modes, navigation, data collection, and other desired functions. Functional testing ensures the correct operation of the system and identifies any potential deficiencies or deviations from requirements.

- Optimization: The integration process should also focus on optimizing the system's efficiency. This includes fine-tuning and optimizing control algorithms, data processing, and other computational processes. The goal is to achieve minimal computation and energy consumption while maximizing the robot's performance.

- Documentation and user manual: Once all components are integrated, it is crucial to create documentation and a user manual. These provide operators and technical support personnel with a comprehensive understanding of the robot's operation, functionality, capabilities, and operational requirements. The documentation may include technical specifications, troubleshooting guides, and guidelines for safe operation.

In summary, integrating all the components of an in-pipe mobile robot is a significant step that requires careful attention to mechanical, electronic, and software aspects. It also involves thorough testing, validation, and documentation to ensure the robot's successful operation and usability.

The process of integrating all the components of In-pipe Robot v1.0 to ensure effective collaboration and cooperation between various professionals and teams is referred to as the iterative and collaborative process that requires interdisciplinary communication and cooperation. Specifically, it involves functional integration tasks and the ability to successfully execute assignments in integration phases. This allows for the creation of a functional and efficient mobile robot with a modular design, capable of performing tasks in different environments.

To define functionality, identify the essential functions that need to be performed by the main control unit. This may include installation of the provided module, gas detection, protection against obstacles and other necessary functions.

In order to eliminate certain limitations, the development of In-pipe Robot v2.0 was initiated with the aim of eliminating certain shortcomings. In-pipe Robot v2.0 was manufactured using a 3D printer and flexible materials for its chassis. The main objective was to reduce the size of the unit and make modifications to the robot's legs.

9 Kinematic analysis of the robot

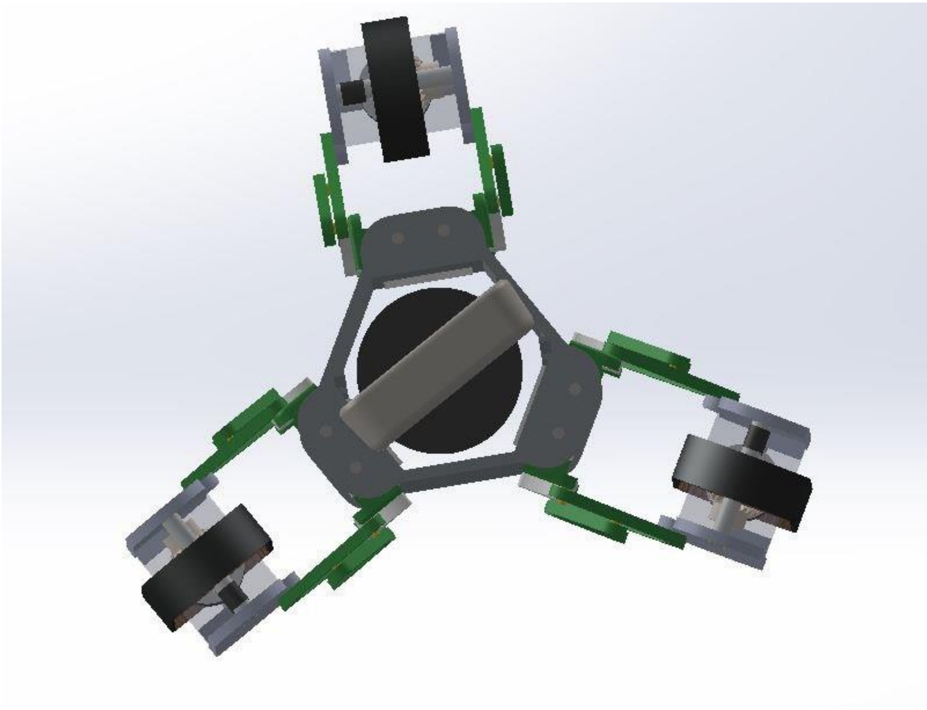

Figure 9.1.1 – Robot with text leg-1, 2, 3

In the analysis of the robot's kinematics, a system of coordinate axes is established to define it’s motion. A Cartesian coordinate system defined, where the Z-axis represents the direction of the pipe, the X-axis shows the normal direction of the ground, and the Y-axis represents the common direction of the plane (Fig. 28). Subsequently, a coordinate system specific to the robot itself is established. The robot consists of three legs: leg-1, leg-2, and leg-3. leg-1 is consistently aligned with the X-axis of the robot's coordinate system, while the Z-axis shows the progressive direction of the robot.

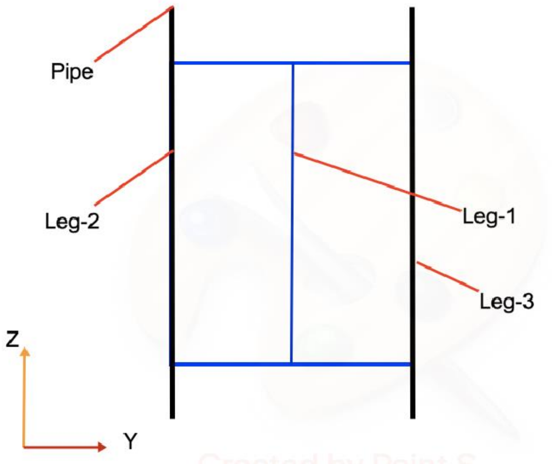

Figure 9.1.2 – Junction between the crawler modules and pipe wall

To analyze the limitations within a bent pipe, the robot's default operational state in a straight pipe is considered. Focusing on a particular section of the pipe, if we treat the robot's track as a rigid body and disregard the track's width, we observe three points of contact between the robot and the inner wall of the pipe on that section. To simplify the representation, we abstract the robot's shape as a rectangle and examine its motion from a top-down perspective, as illustrated in Figure 29. The boundaries of the rectangle's left and right sides correspond to robot leg 3 and leg 2, respectively, while the center line of the rectangle represents leg 1. Within the straight pipeline, these boundaries also serve as contact points between the robot and the pipeline. Additionally, the robot's center coincides with the central axis of the pipeline. It is important to note that the velocities of the three robot legs remain constant. V1, V2, and V3 represent the velocities of legs 1, 2 and 3, respectively, and V the center velocity of the robot.

$$V1 = V2 = V3 = V, \tag{10}$$

A simulation using Solidworks has been conducted to analyze the behavior of the proposed robot under different conditions. The simulation considers factors such as body-to-body contact, motor RPM, and spring stiffness. Two scenarios were simulated: one with the wheels aligned and another with the wheels offset by 120 degrees.

In the first scenario, the robot is placed inside a 300mm-diameter pipeline and travels a distance of 600mm. After this, the inner diameter of the pipeline decreases by 10mm, resulting in an overall diameter of 290mm. This change in diameter tests the robot's ability to adapt to different pipeline sizes. The robot then passes through a straight pipe before encountering a 90° curved elbow. After exiting the curved pipe, it enters another straight pipe before exiting the pipeline. This simulation scenario assesses the robot's performance in traversing pipes with varying diameters and curved sections.

The simulations vary only in the wheel mounting angle, while other parameters such as gravity, motor speed, solid body contact, and spring stiffness remain consistent. The motor operates at a speed of 25 RPM and provides ample torque, allowing the robot to navigate through pipe curves and rough surfaces effortlessly.

The robot is equipped with wheels positioned 120 degrees apart from each other, measured from the centers of the wheels to the central axis of the robot body. This arrangement creates a motion singularity, which occurs when the wheels are homogeneously mounted. To accommodate the varying shape of the pipeline, the robot's three legs are connected through a spring-supported junction, allowing independent compression as they pass through the pipeline.

Inside curved pipelines, the motion singularity becomes apparent. While wheel 1 rotates at a higher angular velocity, wheels 2 and 3 remain stationary. However, when the robot attempts to enter a curved pipeline, wheel 3 loses contact with the pipe wall, indicating that its angular velocity should have been higher as it traversed the concave region of the pipe. This loss of contact is due to the constant magnitude of wheel 3's angular velocity.

During the robot's movement through a 300 mm pipeline, the wheels experience a maximum force of approximately 11.25 N. When the pipeline's inner diameter decreases to 290 mm, wheels 1 and 2 encounter increased forces, while wheel 3 experiences a decrease in forces. Upon entering the curved pipeline, wheel 3 loses contact, resulting in a spike in force due to the compression of the remaining wheels on the spring. The spring force causes the wheels to push the robot backward, causing wheel 3 to collide with the inside of the pipe and generate a significant force spike.

The springs located at the front and back of the robot, referred to as springs 1 and 2 respectively, generate forces ranging from 12 to 20 N when the robot traverses a pipeline with a 300 mm inner diameter. As the inner diameter reduces to 290 mm, the force generated by springs 1 and 2 approaches 25 N. Motion singularity prevents the robot from successfully navigating the curved pipeline, resulting in a decrease in force exerted by spring 1. This motion singularity also causes the back half of the robot to exert a slight push due to inertia, resulting in compression of the legs and the generation of a strong initial force of approximately 50 N, gradually decreasing over time.

Inside a straight 300 mm pipeline, the robot maintains an average linear velocity of 0.1 m/s. When the pipeline's inner diameter decreases to 300 mm, the linear speed of the robot fluctuates between 0.1 and 0.15 m/s. However, when the robot attempts to enter the curved pipeline, the motion singularity causes a sharp decline in linear velocity, preventing successful entry.

10 Robot comparison

The in-pipe robot presented exhibits several unique features and capabilities compared to other existing in-pipe robots. Firstly, the in-pipe robot incorporates a compact design, allowing it to navigate through narrow pipelines with ease. The use of a compact board, mounted on the center module of the robot, enables efficient control and operation of the system. This compactness is a notable advantage as it minimizes the risk of the robot getting stuck or causing damage to the pipe walls during traversal.

In terms of sensing and diagnostics, the in-pipe robot stands out with the integration of Intel RealSense depth camera (LIDAR) alongside the TOF sensor. This combination provides a comprehensive and accurate assessment of the pipe condition in 3D. By leveraging Python libraries such as Open3D, PyntCloud, and PDAL, the robot can effectively process and analyze the Lidar data, enabling the visualization of pipe networks, detection of anomalies or damages, and overall assessment of pipe conditions. This integration of advanced sensing technologies and data processing capabilities enhances the robot's capabilities in terms of inspection and maintenance tasks.

Furthermore, the in-pipe robot incorporates a well-designed circuit board that includes an Arduino Nano for control, a DC motor driver (drv8833) for efficient motor control, and a DC-DC converter to supply power to the Arduino Nano and the driver. The inclusion of chips for easy sensor and part replacement enhances the robot's versatility and maintenance convenience. The incorporation of resistors on the board demonstrates a meticulous approach to electrical design, ensuring proper functioning and protection of the components.

When compared to other in-pipe robots, the in-pipe robot's unique combination of compact design, advanced sensing capabilities, and efficient circuitry sets it apart. The ability to generate 3D models of pipes, analyze pipe conditions, and detect defects using Lidar data processing distinguishes the in-pipe robot in terms of accuracy and comprehensive inspection. The thoughtful design of the circuit board ensures optimal performance and easy maintenance, contributing to the robot's reliability and longevity.

Overall, the in-pipe robot demonstrates a well-rounded approach to inspection and maintenance tasks in pipeline environments. The integration of advanced technologies, careful circuit design, and attention to detail make it a competitive solution for assessing pipe conditions, detecting anomalies, and ensuring efficient operations in various pipeline systems.

10.1 Overview of robot analogues

In the field of pipeline inspection and maintenance, in-pipe robots have emerged as essential tools for assessing the condition of pipelines, conducting repairs, and ensuring the smooth operation of critical infrastructure. These robots are specifically designed to navigate through the internal passages of pipes, carrying out various tasks while minimizing the need for costly and disruptive manual interventions.

In-pipe robots come in a wide range of configurations and designs, each tailored to address specific challenges and requirements in different pipeline applications. These robots are equipped with advanced sensors, cameras, and specialized tools that enable them to capture data, detect anomalies, and perform necessary maintenance or repair tasks. They are designed to adapt to various pipe configurations, including bends, junctions, and narrow passages, which would otherwise be difficult for human operators to access.

10.1.1 Pipe Inspection Gauge

The PIG robot, a well-known and widely used commercial robot in the field of pipeline inspection, operates in a unique and passive manner. It takes advantage of the fluid pressure present within pipelines to propel itself forward. This propulsion mechanism eliminates the need for an external power source or active locomotion systems, making the pig robot an efficient and cost-effective solution for inspecting pipelines with large diameters.

Designed to fit within the pipeline dimensions, the pig robot is inserted into the pipeline through an access point or launch station. Once inside, it relies on the fluid flow within the pipeline to move forward. The pressure difference between the front and back of the robot generates the necessary force for propulsion. As the fluid flows through the pipeline, it pushes the pig robot along the pipe, allowing it to traverse long distances without the need for additional energy inputs.

The pig robot is equipped with a range of sensors and inspection tools that capture vital information about the pipeline's condition. These sensors can include ultrasonic or electromagnetic sensors to detect wall thickness variations, magnetic flux leakage detectors to identify corrosion or defects, or even high-resolution cameras for visual inspection. The data collected by these sensors is then transmitted to an external control and analysis system for further evaluation.

Due to its passive operation, the pig robot is especially suitable for inspecting pipelines with large diameters, such as those found in oil and gas transmission or municipal water supply networks. These pipelines often stretch over vast distances and can be challenging to access for routine inspection and maintenance. By utilizing the fluid pressure for propulsion, the pig robot can travel long distances, thoroughly inspecting the interior of the pipeline and providing valuable insights into its structural integrity, potential defects, or areas requiring maintenance or repair.

The pig robot's passive operation not only reduces the complexity of the robot itself but also minimizes the impact on the fluid flow within the pipeline. This makes it a safe and non-disruptive inspection method, as it does not interfere with the normal operation of the pipeline or require shutdowns during inspection procedures.

In summary, the PIG robot's passive operation, propelled by the fluid pressure within pipelines, offers an effective and widely adopted solution for inspecting pipelines with large diameters. Its ability to autonomously traverse long distances while capturing critical data about the pipeline's condition makes it an invaluable tool for ensuring the integrity and safety of these vital infrastructure systems.

10.1.2 The walking type robot

The walking type of in-pipe robot is a remarkable innovation in the field of robotic inspection and maintenance. Unlike other robot types, the walking robot is equipped with articulated legs that enable it to perform complex and sophisticated movements within the confined spaces of pipelines. These articulated legs mimic the walking motion of animals, providing the robot with enhanced maneuverability and adaptability to various pipe configurations.

The walking robot's articulated legs typically consist of multiple joints, allowing for a wide range of motion and flexibility. This enables the robot to navigate through bends, junctions, and narrow passages that would otherwise pose significant challenges for other robot types. By mimicking the locomotion of living organisms, such as insects or reptiles, the walking robot can effectively traverse uneven surfaces, climb obstacles, and maintain stability in dynamic environments.

The articulated legs are usually equipped with specialized sensors, such as force sensors or tactile sensors, which provide feedback on the robot's interaction with the pipe walls. This feedback allows the robot to adjust its movements and adapt to the changing pipe conditions, ensuring efficient and safe operation.

The walking type of in-pipe robot is particularly useful in situations where precise inspection or maintenance tasks are required. Its ability to perform complex movements enables it to access and examine hard-to-reach areas within the pipeline, ensuring thorough inspections and accurate assessments of the pipe's condition.

Moreover, the walking robot's sophisticated locomotion capabilities offer the potential for advanced functionalities beyond inspection. For example, it could be equipped with additional tools or modules, such as cleaning brushes or repair mechanisms, to perform maintenance tasks directly within the pipeline. This versatility makes the walking type of in-pipe robot a highly valuable and versatile solution for various applications, including pipeline inspection, maintenance, and even intervention tasks.

Overall, the walking type of in-pipe robot, with its articulated legs and advanced locomotion capabilities, represents a significant advancement in the field of robotic pipeline inspection and maintenance. Its ability to perform complex movements and adapt to different pipe configurations opens up new possibilities for efficient and precise operations within pipelines, contributing to enhanced safety, cost-effectiveness, and reliability in the maintenance of critical infrastructure.

10.1.3 The inchworm type is typically used for pipelines with very small diameters.

The inchworm type of in-pipe robot is specifically designed for pipelines with very small diameters. This specialized robot is named after the unique movement pattern it employs, which resembles the crawling motion of an inchworm. The inchworm robot's compact and elongated body allows it to navigate through tight and narrow spaces, making it ideal for inspecting and maintaining pipelines with limited access. Due to their small size and slender structure, inchworm robots can maneuver through pipelines that would be challenging for larger robot types. They are capable of traversing pipelines with diameters as small as a few centimeters. This enables them to access areas that would otherwise be inaccessible to other robot designs.

The inchworm robot's crawling motion involves extending its body forward by anchoring one end and then contracting the body to pull the other end forward. This movement is reminiscent of how an inchworm moves by elongating and contracting its body segments. The robot typically employs a combination of mechanical mechanisms, such as extendable legs or flexible segments, to achieve this motion. By utilizing the inchworm type of robot, pipeline operators can perform thorough inspections and maintenance tasks in pipelines with very small diameters. The robot's ability to navigate through confined spaces ensures that critical areas within the pipeline can be accessed and examined accurately.

In addition to inspection, inchworm robots can also be equipped with various sensors and tools to carry out specific tasks. These may include cameras for visual inspection, sensors for detecting leaks or blockages, or even specialized modules for cleaning or repair operations. The inchworm type of in-pipe robot plays a vital role in industries where small-diameter pipelines are prevalent, such as microelectronics, medical devices, or telecommunications. Its unique design and maneuverability allow for efficient and precise operations in these challenging environments.

In summary, the inchworm type of in-pipe robot is tailored for pipelines with very small diameters. Its compact size, elongated body, and crawling motion enable it to access and navigate through tight spaces. This specialized robot design facilitates thorough inspections and maintenance tasks in pipelines where larger robots cannot operate effectively. By utilizing inchworm robots, industries can ensure the integrity and reliability of their small-diameter pipelines, leading to improved operational efficiency and reduced risks.

10.1.4 The screw type robot.

The screw type of in-pipe robot is a notable innovation in the field of pipeline inspection and maintenance. This robot design takes inspiration from the concept of a screw, utilizing a helical shape to enable movement and propulsion within the pipeline. The screw-type robot is particularly well-suited for pipelines with straight sections and relatively large diameters.

The screw-type robot consists of a cylindrical body with helical threads or fins wrapped around its exterior. These helical threads mimic the design of a screw, allowing the robot to rotate and create a propulsive force against the inner wall of the pipe. By rotating its body in a controlled manner, the screw-type robot can move forward or backward within the pipeline.

One of the advantages of the screw-type robot is its ability to generate a significant amount of thrust, enabling it to traverse long distances efficiently. The helical threads provide a reliable grip on the pipe's inner surface, ensuring effective propulsion and preventing slippage during movement.

To enhance its functionality, the screw-type robot can be equipped with various sensors and tools. For example, it can incorporate cameras or imaging sensors to capture visual data for inspection purposes. Additionally, it can be equipped with sensors to detect anomalies, such as leaks or blockages, along the pipeline. This combination of propulsion and sensing capabilities allows the screw-type robot to perform thorough inspections and identify potential issues within the pipeline.

The screw-type robot is particularly useful in pipelines with relatively large diameters and straight sections, such as those found in oil and gas, water distribution, or sewage systems. Its efficient propulsion mechanism and ability to cover long distances make it well-suited for inspecting and maintaining these types of pipelines.

In summary, the screw-type in-pipe robot utilizes a helical shape to enable movement and propulsion within pipelines. Its screw-like design allows for efficient traversal of straight sections and relatively large diameter pipes. With its ability to generate thrust and carry various sensors, the screw-type robot is a valuable tool for inspecting and maintaining pipelines in industries that rely on efficient and reliable transportation of fluids or gases.

Most in-pipe robots utilize mechanisms derived from one or a combination of the basic types mentioned above. The specific goals of an in-pipe robot closely relate to the task requirements of the particular application. The primary objective of an in-pipe robot is to be able to explore and navigate within its designated task space.

11. Visualization of data using a Python

```
import numpy as np
import matplotlib.pyplot as plt

# Input data containing radius (r) and degrees (d)
data = [[200, 0.00], [200, 0.09], [200, 0.18], ...]

# Extracting r and d values from the data
r = [item[0] for item in data]
d = [item[1] for item in data]

# Converting degrees to radians
radians = [deg * 11.0599 * np.pi / 180 for deg in d]

# Converting r and radians lists to numpy arrays
r = np.array(r)
theta = np.array(radians)

# Calculating x and y coordinates using polar coordinates
x = r * np.cos(theta)
y = r * np.sin(theta)

# Creating a figure and a subplot with polar projection
fig = plt.figure()
ax = fig.add_subplot(1, 1, 1, projection='polar')

# Plotting the lines
for i in range(len(r) - 1):
    if r[i] < 160:
        ax.plot([theta[i], theta[i+1]], [r[i], r[i+1]], color='red')
    else:
        ax.plot([theta[i], theta[i+1]], [r[i], r[i+1]], color='blue')

# Setting the radial tick values
ax.set_rticks(np.arange(0, max(r), 10))

# Setting the title of the plot
ax.set_title('In-pipe view')

# Adding a notification text if there are red lines (r < 160)
red_lines = [i for i in range(len(r) - 1) if r[i] < 160]
if len(red_lines) > 0:
    notification = "Red lines are less than 170mm"
```

```
    ax.text(np.mean(theta[red_lines]), np.mean(r[red_lines]), notification,
            fontsize=12, color='black', ha='center', va='bottom', weight='bold')

# Displaying the plot
plt.show()
```

The given code snippet demonstrates a visualization of data using a polar plot in Python. Here's a description of the code with comments:

```python
import numpy as np
import matplotlib.pyplot as plt

# Input data containing radius (r) and degrees (d)
data = [[200, 0.00], [200, 0.09], [200, 0.18], ...]

# Extracting r and d values from the data
r = [item[0] for item in data]
d = [item[1] for item in data]

# Converting degrees to radians
radians = [deg * 11.0599 * np.pi / 180 for deg in d]

# Converting r and radians lists to numpy arrays
r = np.array(r)
theta = np.array(radians)

# Calculating x and y coordinates using polar coordinates
x = r * np.cos(theta)
y = r * np.sin(theta)

# Creating a figure and a subplot with polar projection
fig = plt.figure()
ax = fig.add_subplot(1, 1, 1, projection='polar')

# Plotting the lines
for i in range(len(r) - 1):
    if r[i] < 160:
        ax.plot([theta[i], theta[i+1]], [r[i], r[i+1]], color='red')
    else:
        ax.plot([theta[i], theta[i+1]], [r[i], r[i+1]], color='blue')

# Setting the radial tick values
ax.set_rticks(np.arange(0, max(r), 10))
```

```
# Setting the title of the plot
ax.set_title('In-pipe view')

# Adding a notification text if there are red lines (r < 160)
red_lines = [i for i in range(len(r) - 1) if r[i] < 160]
if len(red_lines) > 0:
    notification = "Red lines are less than 170mm"
    ax.text(np.mean(theta[red_lines]), np.mean(r[red_lines]), notification,
            fontsize=12, color='black', ha='center', va='bottom', weight='bold')

# Displaying the plot
plt.show()
```

The code begins by importing the necessary libraries: `numpy` for numerical operations and `matplotlib.pyplot` for data visualization. The input data contains pairs of radius (r) and degrees (d) values. These values are extracted from the data list.

The degrees are converted to radians using the formula `deg * 11.0599 * np.pi / 180`, and the radius and radians lists are converted to numpy arrays. The x and y coordinates are calculated using polar coordinate transformations.

A figure and a subplot with a polar projection are created. The lines are plotted based on the radius values, with lines below 160 marked in red and others in blue. Radial tick values are set, and the plot is titled as "In-pipe view".

If there are red lines (r < 160), a notification text is added to indicate this condition. The text is placed at the average position of the red lines.

Finally, the plot is displayed using `plt.show()`. This code segment provides a visual representation of the data in a polar plot, highlighting specific conditions and providing informative notifications.

Controlling 3 DC motors using the DRV8833L motor driver and a joystick with Arduino

```
#include <AFMotor.h>

AF_DCMotor motor1(1);  // Motor connected to M1 terminal
AF_DCMotor motor2(2);  // Motor connected to M2 terminal
AF_DCMotor motor3(3);  // Motor connected to M3 terminal

int joyXPin = A0;      // Joystick X-axis analog pin
int joyYPin = A1;      // Joystick Y-axis analog pin

void setup() {
  // Set the motor speed
  motor1.setSpeed(255);
```

```
  motor2.setSpeed(255);
  motor3.setSpeed(255);

  // Initialize the serial communication
  Serial.begin(9600);
}

void loop() {
  // Read the joystick position
  int joyX = analogRead(joyXPin);
  int joyY = analogRead(joyYPin);

  // Map the joystick position to motor speed (-255 to 255)
  int motorSpeed1 = map(joyX, 0, 1023, -255, 255);
  int motorSpeed2 = map(joyY, 0, 1023, -255, 255);
  int motorSpeed3 = map(joyY, 0, 1023, -255, 255);

  // Control the motors based on joystick position
  motor1.run(motorSpeed1 > 0 ? FORWARD : BACKWARD);
  motor1.setSpeed(abs(motorSpeed1));

  motor2.run(motorSpeed2 > 0 ? FORWARD : BACKWARD);
  motor2.setSpeed(abs(motorSpeed2));

  motor3.run(motorSpeed3 > 0 ? FORWARD : BACKWARD);
  motor3.setSpeed(abs(motorSpeed3));

  // Print the motor speeds to the serial monitor
  Serial.print("Motor 1 Speed: ");
  Serial.print(motorSpeed1);
  Serial.print(", Motor 2 Speed: ");
  Serial.print(motorSpeed2);
  Serial.print(", Motor 3 Speed: ");
  Serial.println(motorSpeed3);

  delay(100);
}
```

Code for controlling 3 DC motors using the DRV8833L motor driver and a joystick with Arduino. I'll provide a description of the code with comments:

```
#include <AFMotor.h>

AF_DCMotor motor1(1);  // Motor connected to M1 terminal
```

```
AF_DCMotor motor2(2);  // Motor connected to M2 terminal
AF_DCMotor motor3(3);  // Motor connected to M3 terminal

int joyXPin = A0;      // Joystick X-axis analog pin
int joyYPin = A1;      // Joystick Y-axis analog pin

void setup() {
  // Set the motor speed
  motor1.setSpeed(255);
  motor2.setSpeed(255);
  motor3.setSpeed(255);

  // Initialize the serial communication
  Serial.begin(9600);
}

void loop() {
  // Read the joystick position
  int joyX = analogRead(joyXPin);
  int joyY = analogRead(joyYPin);

  // Map the joystick position to motor speed (-255 to 255)
  int motorSpeed1 = map(joyX, 0, 1023, -255, 255);
  int motorSpeed2 = map(joyY, 0, 1023, -255, 255);
  int motorSpeed3 = map(joyY, 0, 1023, -255, 255);

  // Control the motors based on joystick position
  motor1.run(motorSpeed1 > 0 ? FORWARD : BACKWARD);
  motor1.setSpeed(abs(motorSpeed1));

  motor2.run(motorSpeed2 > 0 ? FORWARD : BACKWARD);
  motor2.setSpeed(abs(motorSpeed2));

  motor3.run(motorSpeed3 > 0 ? FORWARD : BACKWARD);
  motor3.setSpeed(abs(motorSpeed3));

  // Print the motor speeds to the serial monitor
  Serial.print("Motor 1 Speed: ");
  Serial.print(motorSpeed1);
  Serial.print(", Motor 2 Speed: ");
  Serial.print(motorSpeed2);
  Serial.print(", Motor 3 Speed: ");
  Serial.println(motorSpeed3);
```

```
  delay(100);
}
```

The code begins by including the `AFMotor` library, which provides functions for controlling DC motors using the Adafruit Motor Shield. Three `AF_DCMotor` objects are created to represent the motors connected to the M1, M2, and M3 terminals of the motor driver.

The analog pins `joyXPin` and `joyYPin` are defined to read the X-axis and Y-axis positions of the joystick, respectively.

In the `setup()` function, the motor speed is set to its maximum value of 255 using the `setSpeed()` function. Serial communication is also initialized with a baud rate of 9600.

The `loop()` function is where the main control logic is implemented. The joystick positions are read using `analogRead()` and mapped to motor speeds using the `map()` function. The joystick's X-axis position controls the speed of motor 1, while the Y-axis position controls the speed of motors 2 and 3.

The motors' direction (forward or backward) is determined based on the sign of the motor speed. The `run()` function is used to set the motor direction, and the `setSpeed()` function is used to set the motor speed.

The motor speeds are printed to the serial monitor for debugging purposes.

A delay of 100 milliseconds is added at the end of each iteration of the loop to prevent rapid changes in motor speed.

Code allows to control three DC motors using the DRV8833L motor driver and a joystick connected to Arduino. The joystick's X-axis position controls one motor, while the Y-axis position controls the other two motors, providing a simple and intuitive control interface.

Conclusion

Limitations and Future Work

While this dissertation has made significant strides in the development of controlling systems for in-pipe robots, there are certain limitations and areas for future exploration that should be acknowledged:

- Limited Pipe Diameter Range: The controlling system developed in this research has been optimized for a specific range of pipe diameters. However, further investigation is needed to extend the capabilities of in-pipe robots to accommodate a broader range of pipe sizes, including both smaller and larger diameters.

- Environmental Challenges: Although the controlling system has demonstrated effectiveness in controlled laboratory settings, real-world pipeline environments often present additional challenges, such as extreme temperatures, corrosive substances, and varying fluid flow rates. Future work should focus on enhancing the resilience and adaptability of in-pipe robots to operate effectively in diverse and harsh conditions.

- Autonomous Decision-Making: While the controlling system provides precise navigation and sensor integration, there is room for improvement in autonomous decision-making capabilities. Future research could explore advanced artificial intelligence algorithms and machine learning techniques to enable in-pipe robots to make intelligent decisions based on sensor data, environmental factors, and predefined objectives.

- Integration of Additional Sensors: The controlling system presented in this research incorporates specific sensors for obstacle detection and localization. However, the integration of additional sensors, such as gas or chemical sensors, could enhance the in-pipe robots' ability to detect leaks, identify pollutants, or monitor the pipeline's condition more comprehensively.

- Communication and Data Management: While real-time communication capabilities have been introduced, further work can be done to improve the reliability, bandwidth, and efficiency of data transmission between in-pipe robots and the control center. Research could focus on developing secure and robust communication protocols to ensure seamless information exchange.

- Cost and Scalability: The cost of developing and deploying in-pipe robots remains a challenge. Future efforts could concentrate on reducing production costs, improving manufacturing processes, and optimizing the scalability of in-pipe robot systems to make them more accessible and economically viable for widespread adoption in pipeline industries.

- Human-Robot Collaboration: Collaboration between in-pipe robots and human operators is an essential aspect of pipeline inspection and maintenance. Future research should investigate effective human-robot interfaces, training methods, and safety protocols to enhance the interaction and cooperation between humans and in-pipe robots, facilitating efficient and reliable teamwork.

By addressing these limitations and pursuing further research in these areas, the field of in-pipe robotics can continue to advance, providing more robust and versatile solutions for pipeline inspection and maintenance. The exploration of these avenues holds the potential to overcome current challenges and unlock new possibilities, ultimately contributing to the improvement of pipeline infrastructure management and ensuring the safe and efficient delivery of essential resources.

In conclusion, this dissertation has delved into the realm of in-pipe robots and their potential to revolutionize pipeline inspection and maintenance. Through extensive research and analysis, it has become evident that these robots offer significant benefits such as enhanced navigation capabilities, precise sensor integration, robust power management, and diverse robot analogues.

One key takeaway from this research is the remarkable adaptability and maneuverability of in-pipe robots. These robots can navigate through complex pipe configurations, including bends, junctions, and narrow passages, with ease. This capability allows for more efficient and accurate inspections, reducing the reliance on manual interventions and improving overall pipeline maintenance operations.

Additionally, the integration of advanced sensors and control algorithms has proven to be instrumental in enhancing the capabilities of in-pipe robots. The fusion of sensor data, such as TOF sensors and cameras, with sophisticated control algorithms enables precise navigation, accurate localization, and real-time mapping of the pipe's internal structure. This integration empowers operators with valuable insights and facilitates timely decision-making during inspections and maintenance tasks.

Furthermore, the development of robust power management solutions has addressed the limitations surrounding power and energy requirements. By implementing multiple DC motors and utilizing a wired configuration, the in-pipe robots demonstrate efficient operation and extended working ranges. The emphasis on lightweight design also contributes to the robot's agility and minimizes the potential for structural damage within the pipeline.

Finally, exploring various robot analogues has provided a comprehensive understanding of the diverse capabilities and applications of in-pipe robots. Each robot type, whether it be the walking type, inchworm type, or screw type, offers distinct functionalities suited to different pipeline conditions. This versatility expands the possibilities for pipeline inspection and maintenance, allowing for customized solutions based on specific requirements.

In summary, this dissertation highlights the significant potential of in-pipe robots in revolutionizing the pipeline industry. Their adaptability, precise sensor integration, robust power management, and diverse robot analogues position them as valuable assets for efficient and effective pipeline inspection and maintenance. The findings of this research contribute to the advancement of in-pipe robotics and pave the way for further exploration and innovation in this exciting field.

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