DESIGN AND DEVELOPMENT OF THE SNAKE TYPE ROBOT JOINT FOR PIPELINE INSPECTION

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Requirement for the Degree of Bachelor of
Engineering (Electronics)

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DEDICATION

I express my profound gratitude to the Divine Allah, whose unwavering guidance and boundless grace have endowed me with the mental acuity, fortitude, and protection essential for undertaking this scholarly endeavor.

My deepest appreciation goes to my beloved parents, whose unwavering support, encouragement, and provision of both emotional and financial assistance have been the cornerstone of my perseverance. Their invaluable guidance and unwavering presence have been a constant source of inspiration, fostering within me the resilience and serenity needed to pursue this project diligently.

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Furthermore, I wish to dedicate this project document to my esteemed Supervisor, and the esteemed chairpersons of the Electronic Engineering Department at Quaid-e-Awam University, Larkana, whose mentorship, guidance, and invaluable insights have been instrumental in shaping the trajectory of this academic pursuit.

CERTIFICATE

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I hereby confirm that the content showcased in this project/thesis was entirely composed by the subsequent students under the guidance of Dr. Khalil M. Zuhaib Kamboh and has been submitted to and approved by the examination panel for the final-year thesis/project.

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ABSTRACT

This thesis presents a comprehensive exploration of our developed multilink articulated robot equipped with specialized spring joints, strategically engineered to optimize adaptability in diverse pipe sizes during inspection and exploration. The primary focus of our design is on enabling robot to swift adapt to varying pipe structures, emphasizing the utility of holonomic rolling movement over traditional linear motion, particularly beneficial in navigating winding pipes.

The core objective of this project is to design and develop a robot having the potential for achieving superior adaptability and maneuverability in straight pipes, accomplished through the strategic integration of spring joints with reduced actuator dependency. The study delves into the intricate relationship between fewer actuators and the innovative design of spring joints, aimed at enhancing the robot's adaptability while ensuring optimal performance.

By emphasizing the nuanced interplay between design elements and reduced actuator dependency, this thesis aims to advance the understanding of how spring joints contribute to heightened adaptability in multilink articulated robots, specifically tailored for efficient exploration in pipes of varying sizes.

The thesis will also demonstrate experimental findings that highlight the efficiency of our robot joint design when navigating pipelines of varying diameters.

CHAPTER 1

INTRODUCTION

This chapter Introduces the introduction and motivation for the project and presents the aims and objectives for the development of a pipe inspection robot. The chapter also review existing work on the subject, to understand how other researches have tackled the problem, and what technologies exist that can be used to develop a solution.

1.1 Introduction

Pipelines form a crucial part of the way we live today as they are the primary means of transporting many of the resources that we depend on, such as water, gas and oil. There are millions of miles of pipeline throughout the world and they can be found in both domestic and industrial settings. Many of these pipelines are situated underground so as not to affect everyday life. However, this makes repair and inspection of the pipelines a costly and difficult task, especially since many pipelines have not been designed to optimize automatic repair and inspection tasks [1]. Also, because pipelines rarely have any redundancy, the use of conventional inspection and repair methods, which require the flow to be shut off, can often lead to disruption [2]. Without a reliable method of determining the exact location of a problem, large sections of pipeline need to be excavated and this can be made even more difficult if the pipelines are situated in an urban environment, where the repair work can negatively impact daily life. Neglecting the repair work of such pipelines can lead to leakage of valuable product into the environment, which can lead to damage of the surroundings, expensive clean-up work as well as a loss of business reputation [3]–[5].

1.2 Motivation for pipeline inspection

Leaks, creaks, corrosion and blockages in water distribution pipelines lead to significant losses of resources; the elimination of such losses is crucial for efficient water resource management. Pipeline distribution networks have been widely used as means of transport of different fluids, including water. Due to corrosion, bad workmanship, cracks or normal wear and damage, water pipeline distribution networks can be subject to significant loss of energy and resources. The Canadian Water Research Institute reports that on average 20% of the treated water is wasted due to losses during distribution [6]. A study on leakage assessment in Riyadh, Saudi Arabia, shows the average leak percentage of the ten studied areas to rise up to 30% [6]. As evident by such reports, losses through leaks, cracks, and corrosion represent a significant portion of the water supply. Such losses make the identification and elimination of leaks crucial for efficient water resource management. In-pipe robots equipped with appropriate sensing capabilities have high potential for accurate, efficient, and inexpensive leak detection. Such robots have been widely explored for leaks, cracks, corrosion, and blockage detection in water distribution systems. They can be deployed to inspect the distribution pipeline network without the need for operator intervention. Due to the advantage of being able to go as close as possible to the problem source, they are best suited for potential highly accurate and reliable pipeline inspection [7].

In order to design a robotic system that will work in the inspection of underground water pipes, it is important to understand the pipes, how they are used, what problems they pose to water companies and how they deal with them. It is also important to review existing work on the subject, to understand how other researches have tackled the problem, and what technologies exist that can be used to develop a solution.

1.3 Pipe Network Environment

1.3.1 Water Pipes

The water pipes themselves are responsible for transporting clean water from the treatment plants all the way to the end consumers. Most water pipes are located underground, generally between 1-3m below the surface. Their sizes vary from 75mm for domestic pipes all the way to greater than 450mm in diameter for main trunk pipes.

Pipes are typically made from concrete, cast iron, and more recently, plastics, such as polyethylene (PE) and polyvinylchloride (PVC). Despite upgrades to plastic piping, many existing water mains are made from iron and lead, with some dating back to the Victorian era [8]. Depending on the pipe material, the pipe may have an external and internal coating for protection. One such coating used for a stainless-steel water pipe involves bitumen for the inner coating and an outer lining of bitumen/fiber-glass [9].

The pipe networks themselves primarily consist of straight sections, with 90° swept bends and tees and vertical sections [10]–[11]. Although there was no information found on the frequency of such features in a pipe network, it is reasonable to assume that all of these features are commonly found. Straight sections will likely occupy the bulk of a pipeline. Whenever a pipeline needs to avoid obstacles underground or change direction, swept bends would be used. Any branch pipes that need to connect to the main trunk pipe would do so via tee-junctions. Although most pipelines are expected to be horizontal, changes in ground elevation or certain underground obstacles would require the pipes to also slope vertically. Figure 1.1 shows several examples of underground pipeline maps. As can be seen from the figure, straight sections, swept bends and tees are very commonly found.

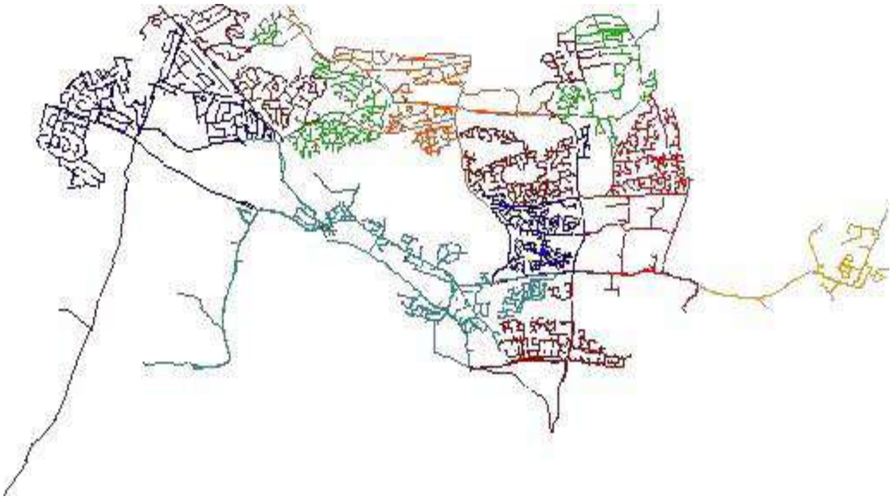

Figure 1.1 Several maps of various underground water pipeline networks [12].

By examining the maps, it becomes apparent that straight sections, tees and bends are common features in an underground water pipe network.

Despite care being taken to make sure that pipes are manufactured and installed correctly and competently, inevitably, leaks will occur. These are caused by a wide variety of different reasons, of which are the following [13]–[17]:

- Corrosion due to the chemical interaction between metal pipes and the soil, or due to the presence of sulphate-reducing and acid producing bacteria.
- Ground movement, which varies from small and gradual shifts (e.g. due to changes in soil temperature and moisture levels and ground settling), to large sudden movements (e.g. from earthquakes).
- The use of high supply pressures, which can exceed the limits of older piping.
- Erosion from existing leaks.
- Damage from third party construction, maintenance and excavation work.
- Inadequate design and construction.
- Ageing infrastructure and poor maintenance.

1.3.2 Pipe Bends and Joints

Pipe networks vary in diameter range, material, and fluid type and can be joined in various methods and configurations. Categorized pipe joint configurations are shown in Figure 1.2. Horizontal sections (1.2A) are considered the baseline for in-pipe complexity, any in-pipe robot should be able to navigate these. Configurations (1.2B-1.2G) are more complex, passing through them requires advanced motion planning techniques.

Valves, are particularly difficult, designs such as plug valves (1.2B) can split the cross-section in two which can hinder full bore robots. Changes in diameter (1.2C) are a common occurrence in unpiggable systems, many robots take measures to prepare for this obstacle specifically. Vertical sections (1.2.D) require a traction method that must also overcome gravity. Elbows (1.2.E) are very commonly encountered and are often described in terms of their bend radius; lower radius bends are tighter harder to navigate. T-Sections (1.2.F) are extremely challenging obstacles due to their lack of wall support; only sophisticated robotic platforms can navigate these.

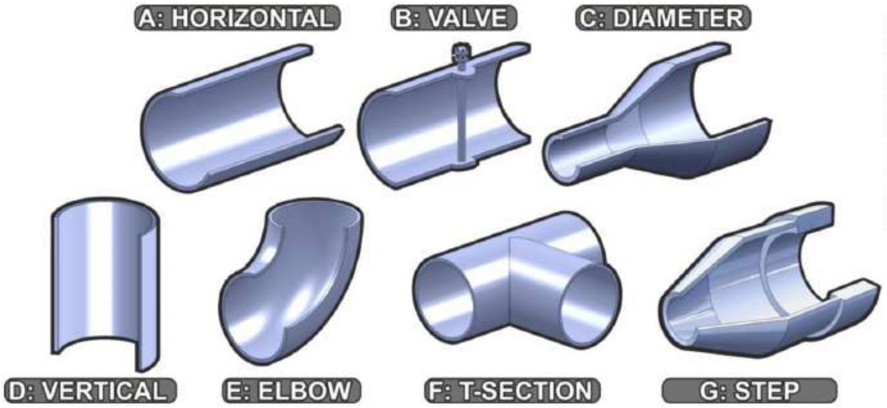

Figure 1.2: The most commonly encountered in-pipe bends and joints in networks A-G

1.4 Robots Locomotion Categories

In-pipe inspection robots have the potential to inspect the condition of these vital assets. Many potential robotic solutions have been proposed to inspect pipelines that are classified by their locomotion mechanism into eight types in Figure 1.3. PIGs (1.3.A) are transport fluid driven devices, although very effective in horizontal pipes they cannot be controlled in complex networks. Wheeled robots (1.3.B) are the simplest method of in-pipe locomotion and can be used in combination with many other element types. Tracked robots (1.3.C), also known as caterpillars, are used as an alternative to wheeled systems, their large surface contact area generates high friction and reduces the chance of losing wall contact. Screw robots (1.3.D) use a spiral inspection path, they perform well in vertical sections and are resistant to slip due to their angled approach, even against an in-pipe flow. Snake robots (1.3.E) take advantage of the length of the pipe, they are generally modular and adaptable to many in-pipe environments. Inchworm robots (1.3.F) are slower than other types but can generally carry higher payloads due to their need for high wall-traction forces, useful in industrial transport tasks where speed is unimportant. Propeller based robots (1.3.G) use transported fluid medium to navigate pipelines and have the advantage of not relying on walls for any movement, however they cannot move in offline systems without fluid. Walking robots (1.3.H) use legs with multiple degrees of freedom (D.O.F) to move, their end effectors have low surface areas, useful in cutting through in-pipe wall contaminants.

Figure 1.3: The eight main elements of in-pipe robotic locomotion

1.5 Review of Pipeline Robots

1.5.1 Existing pipeline inspection robots

There have been a large number of in-pipe robots proposed over the past two decades, all of which can be categorized by their mobility mechanism (Figure 1.3) and level of autonomy.

KANTARO [18] is an example of a fully autonomous wheel type robot. It was developed in Japan for inspection of sewer lines and uses lasers and a camera to autonomously navigate through pipes. Its angled wheels allow it to handle features such as bends or curves in the line. KANTARO was designed to operate in nearly empty sewage pipes with a diameter range of 200-300 mm

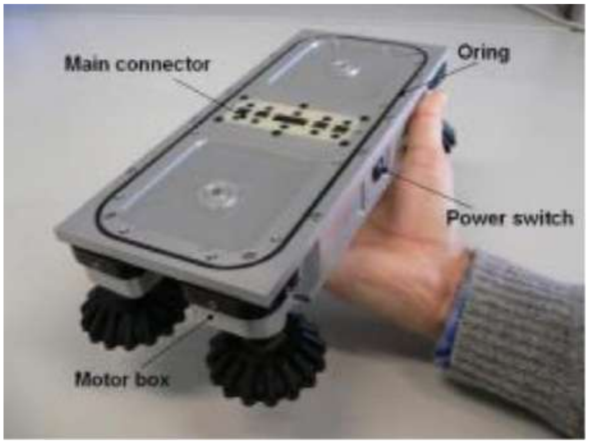

Figure 1.4: KANTARO fully autonomous robot. Image from [18].

An example of an inchworm type robot is shown in Figure 1-4. This robot was developed by Brunete et al. [19] and achieves mobility via a series of 2 degree of freedom servomotors to achieve a snakelike motion. The robot was designed to travel in distribution lines larger than 40mm in diameter.

Figure 1.5: Modular micro robot. Image from [19].

A caterpillar type robot was developed by Kwon et al. [20] which consisted of two modules joined together by a spring and has silicone tracks powered by small DC motors to propel itself down the pipe. This robot utilizes a 4-bar linkage system to contract/expand its tracks to press fit into pipes ranging from 80-100 mm and is operated remotely via a tether link.

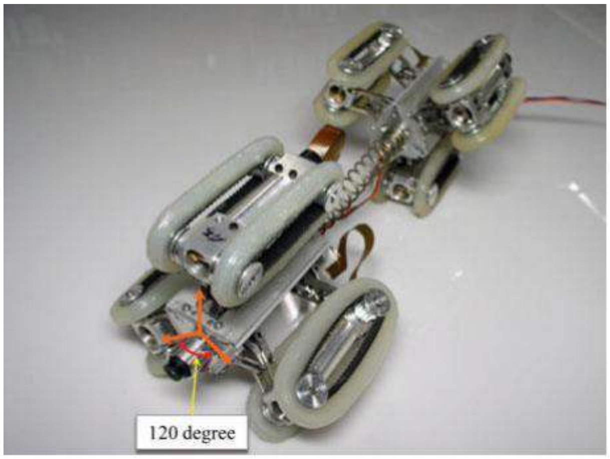

Figure 1.6: Caterpillar type robot proposed by Kwon et al. Image from [20].

The MRINSPECT series of in-pipe robots [21, 22] are examples of robots which combine a wheeled and wall press method to achieve mobility. The latest development from this series is the MRINSPECT VI, which uses differential drive to steer the robot and introduces a transmission system to achieve independent speed control over all of the active wheels on the robot. MRINSPECT VI was designed to inspect 150 mm diameter gas pipes and is controlled by an outside operator via a tether.

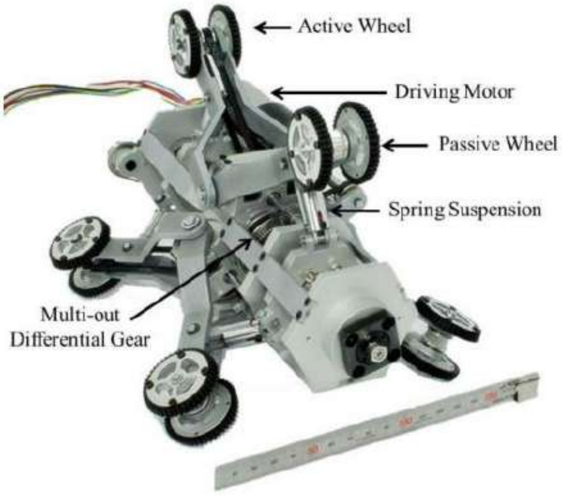

Figure 1.7: MRINSPECT VI in-pipe robot. Image from [22].

The RoboScan inspection robot is a conceptual modular snake-like robot developed by Foster-Miller and GE Oil & Gas under contract from the Northeast Gas Association. It was designed to perform direct in-line inspection of unpiggable natural gas lines while being controlled via a tether. RoboScan uses a unique “triad” mechanism to change its shape and adjust to features in the pipe as it propels itself inside the pipeline.

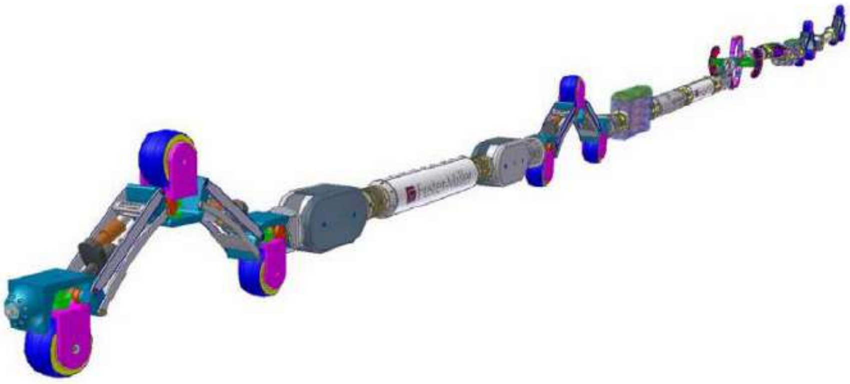

Figure 1.8: RoboScan inspection robot. Image from [23].

The Explorer family of robots by Pipetel Technologies [24] are examples of fully autonomous robots which are operable inside live pipelines. These robots are comprised of multiple modules joined together in series to form a snake-like body and have rigid arms with wheels to press against the wall as it propels itself down the pipeline. These robots are equipped with camera modules and sensors to detect metal loss and inner pipe surface deformation.

Figure 1-9: Prototype of the X-I Explorer robot originally designed at Carnegie Mellon University. Image from [25].

Many other wheeled [26], caterpillar [27], wall-press [28, 29, 30], walking, and inchworm [31] robots have been developed but are not fully covered here. A common feature of many of the robots reviewed is that most are designed for either a specific pipe size or small range of sizes and tend to take up a significant portion of the pipe cross sectional area. Also, because of either their large size or mobility mechanisms many of these robots are not capable of operation in vertical pipes of various diameters.

1.5.2 Existing multilink-articulated wheeled snake robots

Identifying deterioration points in aging pipelines is a very important task to avoid critical leakage and explosion accidents. Till date, researchers and engineers have tried developing inspection robots to look inside narrow pipes where humans cannot enter. The risk of accessing the pipelines, especially those placed underground or at high places, can be avoided if the pipes can be inspected from the inside by robots instead of humans. Recently, highly adaptable in-pipe inspection robots that resemble railway trains and redundant manipulators have been developed. These robots, which are often called snakelike robots, possess rope-like bodies. They are capable of superior performances especially in the bend and branch of pipes due to their rope-like bodies. Multi-segmented and cable-free robot platforms, namely the “MAKRO and KAIRO series” are developed by INSPECTOR SYSTEMS, Rainer Hitzel GmbH, Germany [32]– [34]. These robots wriggle using oblique joints.

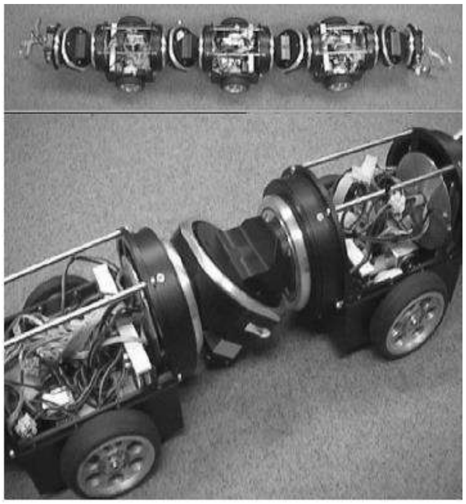

Fig. 1.10. Three middle segments of the fiveve- segment, articulated sewer robot MAKRO (up), and close-up of an active joint (image from [32])

Fig. 1.11. The modular snake-like inspection robot KIRO 3 (image from [34])

They also develop another type of multi-segmented inspection robot called “INSPECTOR” that adapts to vertical pipes. For a while, Schempf et al. have focused on the “Explore” project for inspecting live gas mains [35]. This robot system is untethered, self-powered, and wirelessly controlled.

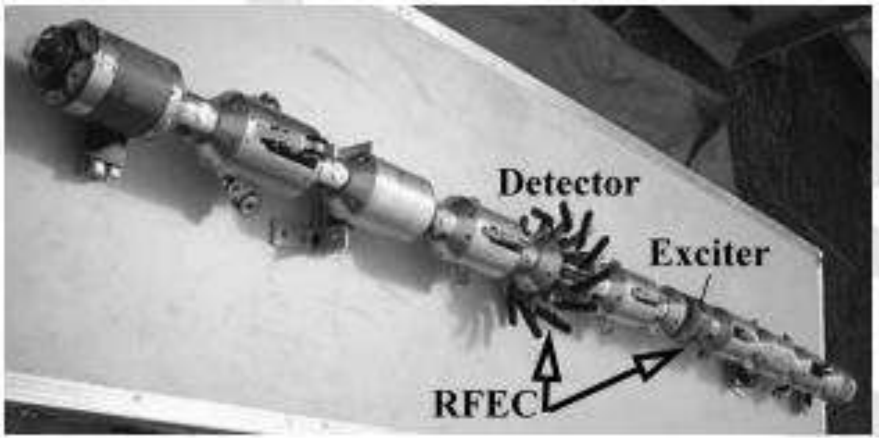

Figure 1.12. Prototype X-II-RFEC platform depicting drive, battery, support, steering, and RFEC sensor module(s) for visual and NDE inspection (image from [35])

Recently, the Explore project has been put to practical use by Pipetel Technologies Inc. Choi et al. are advancing the MRINSPECT project for inspection of gas pipelines. The latest robot, called “MRINSPECT VII,” is equipped with differential mechanisms, and the joints between the segments are backdrivable [36], [37]. INSPECTOR, Explore and MRINSPECT

VII can press against the inner wall of the pipe with expandable active arm mechanisms and can go up the vertical pipes.

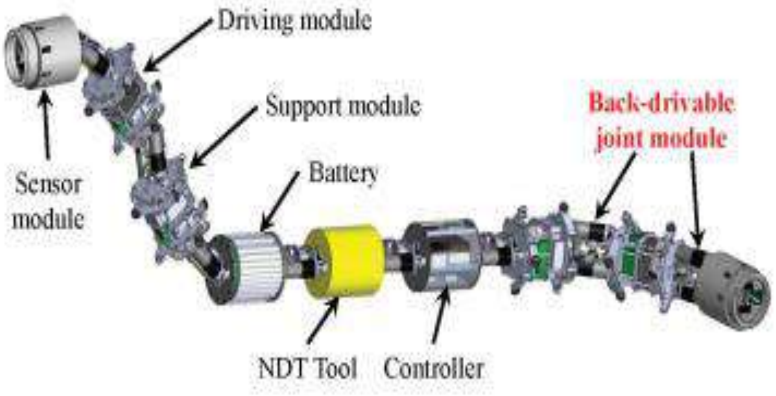

Fig. 1.13. MRINSPECT VI++ integrated with all the modules. (image from [37])

Dertien et al. designed a multilink-articulated wheeled robot called “PIRATE.” Its joints are actuated by motor and torsion springs that clamp the robot in the pipe [38], [39]. Another active joint placed at the center of the robot could twist half of the body to change the steering direction. A different version of the PIRATE series with omni wheels was also reported. It possessed a joint that was passively bent in the pipe by the rubber band that connected the links.

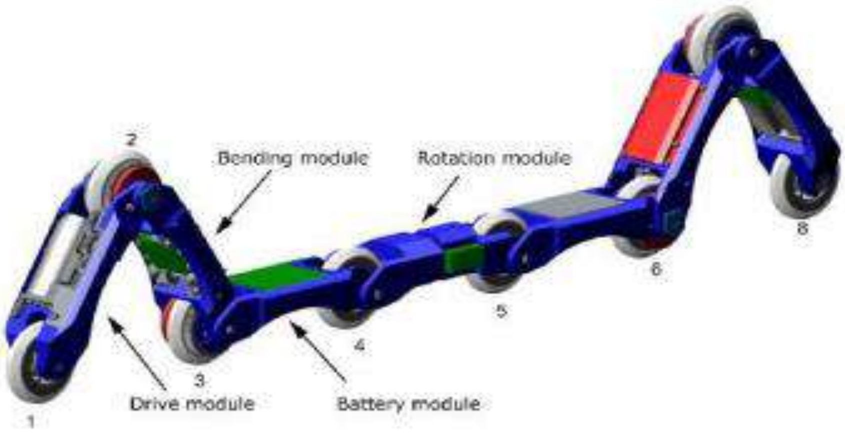

Fig. 1.14: Schematic drawing of the pipe inspection robot. (image from [38])

Hirose et al. proposed the “PIPETRON series” (also called “THES” in some literature), which also adopted the multilink-articulated wheeled mechanism [40], [41]. In the PIPETRON-I, two wires were distributed to bend each joint in the pitch and yaw directions. A wire caused the robot’s wheel to touch the pipe wall. Another wire twists the robot’s body to helically move it in the straight pipe by aligning the steering direction of the robot beforehand.

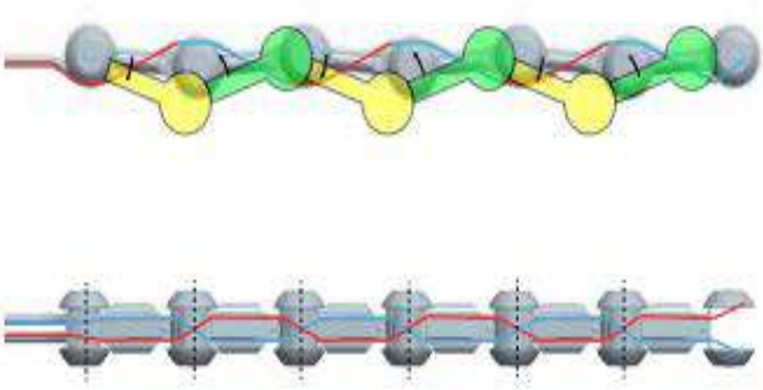

Figure 1.15. PipeTron in “pitch zig-zag” posture (image from [41])

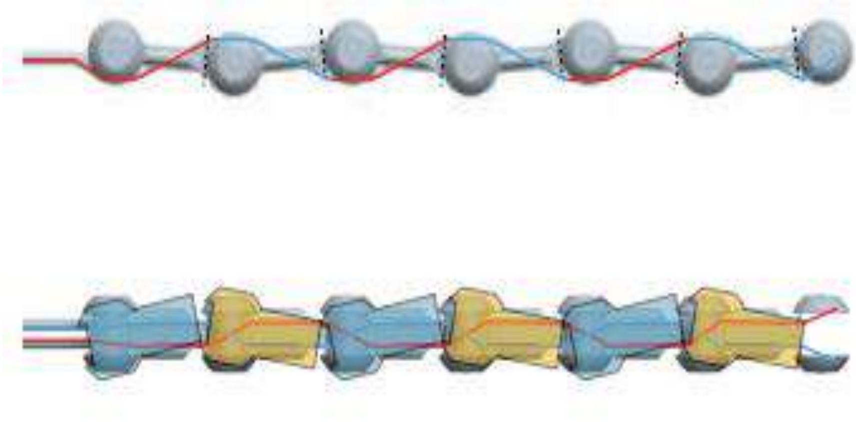

Figure 1.16. PipeTron in “yaw zig-zag” posture (image from [41])

The PIPETRONII was developed as the second generation of the PIPETRON series. It maintained the zigzag shape of the robot using torsion springs mounted at the joints. The latest version of the PIPETRON was also reported. However, due to contractual reasons, concrete information has not been published yet.

Figure 1.17 – PipeTron-II (image from [41])

Transeth et al. proposed a snake-like inspection robot called “PiKo.” The use of the pitch and yaw active joints allowed the robot to steer itself. They also clamped the robot’s body in the pipe [42]. The robots have no expandable arm mechanisms. Instead, they press against the inner wall of the pipe by bending their own bodies, like an inchworm.

Figure 1.18-The PIKo robot (image from [42])

1.6 Our snake type robot

Among the robots, the former and latter types can be categorized as expandable-arm- and body-bending-types. If the space to mount the expandable arm mechanisms is not sufficient, body bending is more feasible for downsizing. Looking back the history of the in-pipe inspection robots, the body bending type named “Pipemouse” was proposed by Foster-miller Inc. in 2004 [43], and its prototype appeared in [44]. Most of the body bending-type robots steer at the bend and branch pipes by three-dimensionally swinging the links or helically moving around the pipe axis. However, to quickly align the steering direction, holonomic rolling movement that eliminates forward and backward movements in the pipe is more useful, especially in the short and winding pipe. The articulated robot that uses omni wheels and can holonomically roll was also reported before [45]. However, due to their small radii, small passive wheels that surrounded the omni wheel were not adaptable in the traveling direction. To solve this shortcoming, we designed a multilink-Articulated Inspection Robot with omni wheels as shown in Fig. 1.19. Omnidirectional mobile robots that have omni wheels achieve a high obstacle adaptability in all planar directions [46]–[48]. Inspired by this, we designed a multilink-Articulated inspection robot with omni wheels. It consists of 3 pairs of omni wheels, the front and back pairs of omni wheels are active and the middle pair of omni wheel is passive. The forward and backward movement is achieved by the two driving actuators and the joint actuation is achieved by the torsion spring. Due to this both the total weight and the cost of the robot could be reduced. Thus, maintenance becomes easier. Therefore, in this thesis, we pursue the possibility of achieving high maneuverability in the pipes with only two driving actuators and springs for body bending.

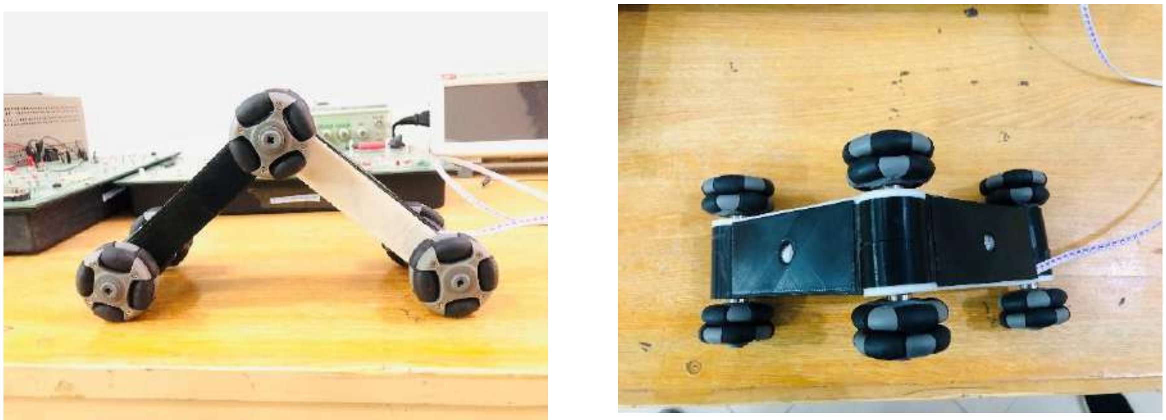

Fig 1.19 Our snake type robot.

1.7 Objectives

Main Objective

- The main goal of this project is to design a robot system that can be used to inspect pipelines of diameter ranging from 4.0 inches to 5.0 inches.

Sub Objectives

- More specifically we are interested to design a robot joint with variable joint angle that can be automatically adjust based on pipe diameter.
- Design a mechanism for driving two set of active wheels with DC geared motor.
- Further design should be such that it can be loaded with different sensors to perform inspection.

1.8 Thesis Organization

The thesis is divided into 5 chapters. The outline of each chapter is presented below:

Chapter 1, Introduces the introduction and motivation for the project and presents the aims and objectives for the development of a pipe inspection robot. The chapter also review existing work on the subject, to understand how other researches have tackled the problem, and what technologies exist that can be used to develop a solution.

Chapter 2, The requirements and specification of the robot are presented, along with the methodology that was followed in developing the robot.

Chapter 3, Presents the steps taken to implement the detailed design. The design is split into two main sections: the mechanical design and the electronic control design. The mechanical design focuses on the design and selection of the various mechanical components that form the robot's structure. This involves the selection of the actuators based on calculations determining their required force, and the design of spring joint and connecting components used to form the robot's structure. The electronic design focuses on the design of the electronic circuitry that is used to control the linear actuators and take measurements from them. This involves the selection of an off-the-shelf motor controller, along with identifying its shortcomings and designing additional circuitry that addresses them.

Chapter 4, The aim of this chapter is to present the experimental work carried out in order to verify the theoretical work done on the prototype described in the previous chapters. This helps to prove that the robot behaves as calculated and allows the real-world practical limitations of the robot to be observed and quantified.

Chapter 5, In this concluding chapter, we navigate through the achievements of developing a pipeline inspection robot. We reflect on its successful design, testing, and execution, while also peering into potential advancements that could revolutionize pipeline inspection methodologies. This chapter encapsulates the culmination of our efforts and paves the way for future enhancements in pipeline inspection robotics.

Chapter 02

Specification and Methodology

In this chapter, the requirements and specification of the robot are presented, along with the methodology that was followed in developing the robot.

2.1 Requirements

From the first chapter, it became clear that snake-type robots have the potential to revolutionize pipeline inspection. We discussed why it's needed, its goals, and where it can be applied [1.5.2]. Now our focus sharpens. We're about to define a precise set of requirements that will serve as the guiding principles for developing our robot. These requirements are like the building blocks, shaping our robot into a smart and adaptable solution for pipeline inspection. Let's see each requirement how it transforms our vision into reality.

- **Articulated Multi-Link Structure:**
  - The robot shall feature a snake-shaped, articulated multi-link structure that provides flexibility and adaptability.
  - The robot's articulated links should allow it to contract and relax, providing maneuverability within pipes of varying diameters.
- **Holonomic Movement capability:**
  - The robot shall exhibit holonomic movement ensuring precise maneuverability and control in straight sections of vertical and horizontal pipes.
- **Adaptation to Varying Pipe Diameters:**
  - The robot shall employ an adaptation technique to automatically adjust its configuration to fit different pipeline diameters within the specified range.
- **Multidirectional Pipe Traversal:**

    - The robot shall move multidirectional (forward and backward) in pipelines and is designed for horizontal and vertical pipe traversal.
- **Robot Actuators:**
    - The robot actuators should provide enough torque and precise control over its movement.

These requirements serve as the cornerstone of our snake like pipeline inspection robot project, guiding the design and development phases. In the subsequent sections of this chapter, we will see the target specifications and methodologies required to meet these requirements, ensuring the successful realization of our innovative robotic solution.

2.2 Target Specifications

The development of such a robot would cover a wide range of different disciplines and skills. For this thesis, it was decided to focus on achieving navigational versatility within pipelines of varying diameters. The robot should seamlessly move through horizontal and vertical pipes without encountering any disturbances, ensuring precise movement in diverse pipeline configurations.

Based on this and the water pipe properties mentioned in the [1.3]. The following specifications were derived that the robot's mechanical design should adhere to:

- **Flexible Articulation:**
    - The robot's multi-link structure should offer a high degree 90° of flexibility, enabling it to adapt to various pipe diameters within the specified range.
- **Holonomic Movement with Omni wheels:**
    - The robot shall exhibit holonomic movement using Omni wheels, ensuring precise maneuverability and control in straight sections of both horizontal and vertical pipes.

- **Automatic Diameter Adaptation:**
    - The robot's adaptation technique should automatically adjust its configuration to fit pipes with different diameters ranging from 4 inch to 5 inch without operator intervention.
- **DC Geared Motor Actuation:**
    - The robot shall utilize DC geared motors for propulsion, allowing precise and responsive movement control.

These target specifications aim to ensure that our snake like pipeline inspection robot excels in navigational versatility, enabling it to inspect pipelines of different diameters and orientations with precision and agility.

2.3 Methodology

Our project to create a Snake-Like Pipeline Inspection Robot followed a step-by-step approach:

- **Literature Review and Problem Formulation**
    - We began by studying existing knowledge to understand the challenges in pipeline inspection.
    - We identified the specific problems we wanted our robot to solve, like inspecting small pipelines effectively.
- **Design Decision**
    - Next, we decided on the robot's design. We aimed for a flexible, snake-like structure that could adapt to different pipe sizes.
- **Actuator Selection**
    - We carefully chose the right actuators (motors) to control the robot's movement.
    - We designed a circuit to ensure these motors worked correctly.
- **3D Design with SolidWorks**
    - Using computer software called SolidWorks; we created a 3D model of our robot. This helped us visualize how it would look and work.

- **Electronics Development**
    - For controlling the robot, we used an analog joystick, an Arduino (a type of computer), and a motor driver circuit. These electronic parts were crucial.
- **Writing control code**
    - We wrote custom computer code to make the motors do what we wanted. This code allowed us to control the robot's movements.
- **Component Procurement and Prototype Assembly**
    - We bought all the parts we needed, like wheels, gears, springs, motors, and electronic components.
    - Then, we put everything together to build the first robot prototype.
- **Test Bed Creation and Experiments**
    - We set up a special testing area to mimic pipeline conditions. This helped us see how well the robot moved and adapted.
    - We ran experiments to check if the robot could do what it was designed for – inspecting pipelines.
- **Thesis Writing**
    - Finally, we documented everything we did in a thesis to share our findings and the journey of creating this innovative robot.

This step-by-step approach ensured we carefully thought through each stage of the project, from research to building and testing, all the way to sharing our knowledge through the thesis.

2.4 Summary

In this chapter, we saw the core aspects of our Snake-Like Pipeline Inspection Robot project. We explored three main areas: requirements, target specifications, and our methodology. Here's what we covered:

We set the rules for our robot. These were the must-haves that defined what our robot must do. Each requirement was carefully thought out, shaping our robot's capabilities.

We set the target specifications which were like our robot's special abilities. We aimed for a robot that could adapt to different pipe sizes, move in small pipelines, and follow the industry's rules.

We followed a step-by-step plan to build our robot. We started with research, selected design, selected parts, created a 3D model, and wrote code to control the robot. We tested it, made experiments, and finally, here we are, documenting our journey in this chapter.

In summary, this chapter was all about setting the rules, defining our robot's superpowers, and sharing our step-by-step plan. It's like making a roadmap for our robot's adventure.

Chapter 03

Detailed Design

This chapter presents the steps taken to implement the detailed design. The design is split into two main sections: the mechanical design and the electronic control design. The mechanical design focuses on the design and selection of the various mechanical components that form the robot’s structure. This involves the selection of the actuators based on calculations determining their required force, and the design of spring joint and connecting components used to form the robot’s structure. The electronic design focuses on the design of the electronic circuitry that is used to control the linear actuators and take measurements from them. This involves the selection of an off-the-shelf motor controller, along with identifying its shortcomings and designing additional circuitry that addresses them.

3.1 Robot overview

Our pipeline inspection robot redefines pipeline assessment. Its articulated design allows it to smoothly navigate varying pipeline configurations. Fitted with 24V DC geared motors and omni wheels, it maneuvers adeptly through horizontal and vertical pipes, ensuring precise traversal. Departing from conventional sensor-based inspection, it leverages joint design and spring-actuated angles for maneuverability. The robot's mechanics, driven by carefully selected actuators, ensure operational efficiency for comprehensive pipeline assessment. Its adaptable structure, with two identical links and a torsion spring system, facilitates seamless movement and articulation control. Auxiliary elements like the extension holder prepare it for future expansions, showcasing a meticulous engineering approach. This robot encapsulates innovation and precision, aiming to transform pipeline inspection, maintenance, and exploration practices.

3.2 Mechanical Design

3.2.1 Actuator selection

In this section, we embark on the critical process of actuator selection for our climbing robot, considering several key factors that significantly impact the robot's performance in its vinyl chloride pipe environment. These factors include the robot's ability to maintain stability, generate motion, and prevent slippage.

To begin, we address the six wheels, four active and 2 passive which are responsible for driving the robot through the vinyl chloride pipe. The total weight of our robot, approximately 1 kg, is distributed among these wheels. Each active wheel, in turn, supports a portion of this weight, calculated as:

$$\frac{\mathrm{W}}{4} = \frac{1\mathrm{kg}}{4} = 0.25 \text{ kg.} \tag{3.1}$$

Since the wheels come into contact with both the top and bottom of the round pipe, the effective normal force (N) for each wheel is now doubled:

$$\text{N} = 2 * \text{W} = 2 * 0.16 \text{ kg} * 9.81 \text{ m/s\^{}2} = 4.9 \text{ N per active wheel.} \tag{3.2}$$

These wheels on a climbing robot serve two purposes: the main purpose is to drive the robot through the environment. The second purpose is to hold the robot in place so that it does not fall.

When it comes to holding the robot in place, the wheels are pressed against the climbing surface in order to generate a frictional force that counteracts the force of gravity and any other forces that might be pulling the robot down [49]. Figure 3.1 shows a free body diagram for a wheel being used for climbing, where P is the force pushing the wheel against the climbing surface, N is the reaction force and W is the weight of the robot pulling down.

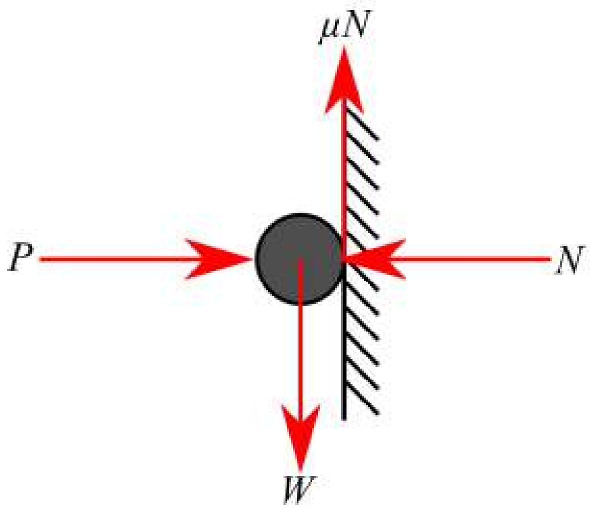

Figure 3.1 Wheeled climbing free-body diagram.

The contact between the wheel and the climbing surface produces a frictional force, μN, which is dependent on the coefficient of friction, μ, between the wheel and the climbing surface, as well as the normal force exerted on the wheel, N. The normal force is in turn dependent on the pushing force, P. This frictional force acts in the opposite direction to the robot's weight, holding the robot in place. If the weight of the robot increases, then the frictional force needs to be increased. The robot can only do this by increasing the force pushing the wheels against the climbing surface.

However, this force is also acting as a load on the wheels, making it more difficult to drive them.

When it comes to drive the robot through its environment by generating motion, the wheels must overcome opposing forces, such as friction, and gravity, which tend to hold the robot in place. These forces can make movement challenging [50].

We calculated all above forces in order to select perfect actuator for our robot which is as under:

Coefficient of friction (μ)

The coefficient of friction (μ) between our wheels and the vinyl chloride pipe is of paramount importance. We assume a specific value of $\mu = 0.5$ (based on a pipe wall of plastic against rubber) for our analysis, which accounts for the materials and environmental conditions.

Calculating Frictional Force on Wheels

We used the fundamental equation for friction to determine the frictional force (F) on each wheel:

$$F = \mu * N$$

Where:

F represents the frictional force in Newton's (N).

μ stands for the coefficient of friction.

N signifies the normal force exerted on the wheel.

For the wheels, the normal force N corresponds to the weight supported by each wheel:

$$F = \mu * W$$

Substituting the values, we obtain,

$$F = 0.5 * 4.9 \text{ N}$$

$$F = 2.45 \text{ N per wheel.} \tag{3.3}$$

Total Frictional Force on Wheels

Our robot is equipped with six wheels four active wheels and two passive wheels, and thus, the total frictional force on these wheels can be calculated as follows:

$$F_t = 6 * F = 6 * 2.45 \text{ N} = 14.7 \text{ N} \tag{3.4}$$

Slippage

The concept of slippage is of particular concern. Slippage occurs when the available frictional force is insufficient to prevent wheel slippage, leading to reduced traction and challenges in forward motion. The robot's ability to navigate the pipe and overcome obstacles relies on finding a delicate balance between the force required for propulsion and the available frictional force.

Criteria for judging slippage

The driving forces should not exceed the maximum static friction to prevent slippage of the driving wheels Therefore, the driving force f should satisfy both:

$$f \leq \mu n1$$

$$f \leq \mu n3$$

simultaneously, where μ denotes static friction coefficient.

To conquer the challenges posed by factors like friction, slippage and gravity, we need an actuator that can handle these complex forces with precision. Our process for choosing the right actuator aims to find the perfect balance between making sure the robot stays firmly in place on the climbing surface and moves forward smoothly. This means selecting actuators that are the right size, have the necessary strength, and come with control features that make everything work together seamlessly.

The choice of actuator is primarily limited by two design factors:

- The required size that will fit in the robot.
- The required force that the robot would need.

3.2.1.1 Actuator size

Selecting an actuator that perfectly fits within the constraints of our robot housings is crucial for ensuring a seamless integration. Our robot housings are designed with specific dimensions, providing a clear framework for the size of the actuator.

Robot Housing

- The robot housing length and width is the maximum space that the actuator can occupy within the structure.

Robot Housing Specifications

1	Length	90	Mm
2	Width	38	Mm
3	Height	25	Mm

Table 3.1 Robot housing specifications

Motor

- Our chosen actuator should fit comfortably within the given housing dimensions without any interference.
- The motor's shaft should align perfectly with the housing to ensure proper functioning.

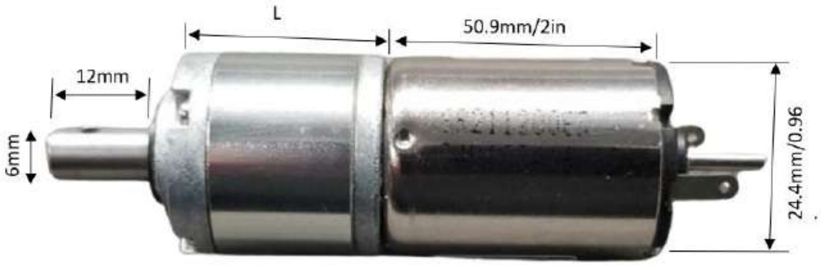

Figure 3.2 DC Geared Motor

Motor Dimension Specifications

1	Motor Length	50.9	Mm
2	Motor Diameter	24.4	Mm
4	Shaft Length	12	Mm

5	Shaft Diameter	6	Mm

Table 3.2 Motor dimension specifications

By adhering to these specific size requirements, we guarantee that the actuator seamlessly integrates with the robot's housing, maximizing both space utilization and overall functionality. This precision in size selection ensures that the actuator becomes an efficient and integral component of our climbing robot.

3.2.1.2 Actuator force

The force produced by the actuator need to be high enough to ensure that the robot is capable of propelling itself through a pipe, maintaining its position inside a pipe and overcoming any forces exerted on it. To calculate the total torque required overcoming the friction and supporting the robot's body weight, considering the adaptation technique, and the values calculated before in (3.2.1), we have:

- Frictional force on each wheel (F) = 2.45 N
- Wheel radius (r) = 0.024 m
- Number of wheels (N) = 6
- Total weight of the robot (Weight) = 1 kg
- Gravitational acceleration (g) ≈ 9.81 m/s² (standard value)

Torque to overcome friction (τ_f) for one wheel (τ):

$$\tau_f = F \times \text{Wheel Radius}$$

$$\tau_f = 2.45\text{ N} \times 0.024\text{ m}$$

$$\tau_f = 0.0588\text{ Nm (or 58.8 mNm) per active wheel} \tag{3.5}$$

Total torque required (τ_{tf}) to overcome friction for all wheels:

$$\tau_{tf} = N \times \tau_f$$

$$\tau_{tf} = 6 \times 0.0588\text{ Nm}$$

$$\tau_{tf} = 0.3528 \text{ Nm (or 352.8 mNm) for all wheels} \tag{3.6}$$

Torque to support the robot's weight (τ_w) for wheels (τ):

$$\tau_w = \text{Weight} \times \text{Wheel Radius} \times g$$

$$\tau_w = 1 \text{ kg} \times 0.024 \text{ m} \times 9.81 \text{ m/s}^2$$

$$\tau_w = 0.23544 \text{ Nm (or 235.44 mNm) per wheel} \tag{3.7}$$

Total torque required to support the robot's weight for all wheels:

$$\tau_{tw} = N \times \tau_w$$

$$\tau_{tw}= 6 \times 0.23544 \text{ Nm}$$

$$\tau_{tw} = 1.41264 \text{ Nm (or 1412.64 mNm) for all wheels} \tag{3.8}$$

Now, add these values to find the total torque required to overcome the friction and support the robot's body weight with the adaptation technique.

$$\tau_{tr} = \tau_{tf} + \tau_{tw}$$

$$\tau_{tr} = 0.3528 + 1.41264$$

$$\tau_{tr} = 1.76544 \text{ Nm (or 1765.44 mNm)} \tag{3.9}$$

So, the total torque required is approximately 1.76544 Nm (or 1765.44 mNm).

So, after calculating the above forces we selected a DC geared motors as an actuator. It has a high reduction ratio 1:84 since norminal torque of motor is 40.2 mNm it can theoretically generate approximately 3.3 Nm.

A DC Geared Motor is an electric motor that uses direct current (DC) to generate mechanical motion. It is equipped with a gearbox, which consists of gears that control the speed and torque of the motor's output. The motor reduction ratio (1:84) helps to reduce the motor's high-speed rotation up to 84 times and increase motors torque up to 84 times, making it suitable for various applications where controlled and precise motion is required.

The reason behind using a DC geared motor with high reduction ratio of 1:84 is because we need low speed and high torque. If we use a normal DC motor without gear system to obtain required torque and speed will have large size and weight.

Motor Force Specifications

Operating conditions

1	Operating Voltage Range	6-24	VDC
2	Rated Voltage	24	VDC
3	Rated Load	1.5	Kgf-cm

Table 3.3 Motor operating conditions

Electrical Characteristics

1	Max No-load Current	0.10	A
2	No-load Speed	142	RPM
3	Rated-load Current	0.20	A
4	Rated-load Speed	113	RPM
5	Min Stall Torque	5.6	Kgf-cm
6	Max Stall Current	1.3	A
7	Output Power At Max Efficiency	1.6	W

Table 3.4 Motor electrical characteristics

Mechanical Characteristics

1	Gear Ratio	1:84	-
2	Net weight	92	Grams

Table 3.5 Motor mechanical characteristics

3.2.2 Gear Selection

We need to transfer torque and speed from one plane to another, specifically from a vertical plane (the motor) to a horizontal plane (the robot's wheel axle). This requirement arises because our motor and wheel axle are positioned perpendicular to each other, we require a mechanism to efficiently transfer the torque and speed generated by the motor from the vertical plane to the wheel shaft at horizontal plane, enabling the robot to move effectively.

Given that our motor and wheel axle are oriented at right angles to each other, we must employ gears capable of connecting at a 90-degree angle to facilitate the transfer of torque and speed between these two perpendicular planes.

For this purpose, we have chosen bevel gears. Bevel gears can be connected at an angle and are particularly suited for transferring torque and speed between planes at a 90-degree orientation. By connecting these bevel gears at 90 degrees to each other, we ensure the effective transmission of torque and speed from the motor to the wheels.

3.2.2.1 Gear Size

We know from the gear selection portion that gears play an important role in facilitating the transfer of torque and speed from one plane to another. Here we will specify the gear sizes which we have chosen and the reason behind these selections.

We are utilizing a total of four gears in our setup because our robot features two active wheels. This means we need to transfer torque and speed from two vertical planes (the motor) to two horizontal planes (the wheel axles). To achieve this, we have arranged four bevel gears, connected in pairs at 90-degree angles.

The two bevel gears connected to the motor in the vertical plane have identical inner diameters of 6mm each. This inner diameter matches the 6mm shaft of the motor we are using, ensuring a proper fit and efficient power transfer.

Conversely, the two bevel gears connected to the wheel axles in the horizontal plane share a common inner diameter of 4mm each. This inner diameter corresponds to the 4mm diameter of our wheel axles, ensuring a snug fit and effective power transmission.

Additionally, all four bevel gears in our configuration possess the same outer diameter, which measures 20mm each. This uniform outer diameter ensures consistent performance and balanced power transfer. To summarize, we are using four gears in total: two with a 6mm inner diameter to match the motor shaft and two with a 4mm inner diameter to match the wheel axles, all with a common outer diameter of 20mm.

S.NO	Gear Inner Diameter	Gear Outer Diameter	No Of Gears
1	6mm	20mm	1 Pair
2	4mm	20mm	1 Pair

Table 3.6 Bevel gear dimensions

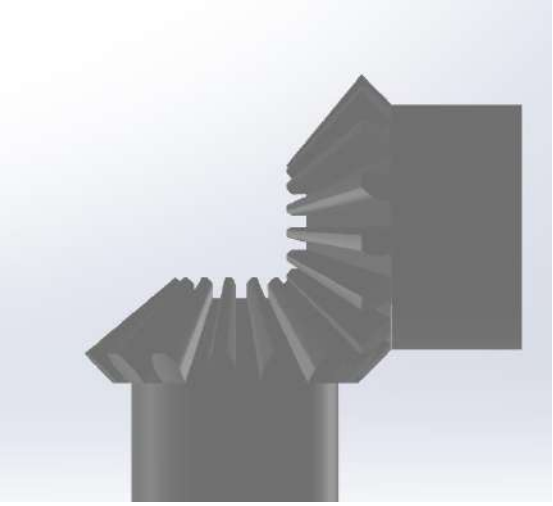

Figure 3.3: Bevel Gears connected at 90°

3.2.2.2 Gear Ratio

From the above discussion we understood the importance of bevel gears in our project. We are using 4 bevel gears two with 6mm inner diameter and two with 4mm inner diameter and outer diameter are same for all four gears as 20mm. Now in this portion we are going to discuss the reduction ratio for all four gears.

In our design, we have chosen to use bevel gears with a 1:1. The reason behind this choice is straightforward; we aim to transfer the exact same torque and speed generated by the motor in the vertical plane to the wheel axle in the horizontal plane. By implementing a 1:1, we ensure that there is no alteration in the power characteristics as it moves from the motor to the wheels. This direct transfer of torque and speed is fundamental to achieving precise and consistent performance in our robot.

3.3 Joint Design

In the joint design of our multilink articulated robot, the structure comprises two links that form a flexible joint when connected. One link features an extended part as shown in figure 3.4, while the other accommodates this extension as shown in figure 3.5, enabling smooth rotation between the links. To facilitate frictionless movement, bearing was integrated between the links.

For maintaining extension between the links, we incorporated eight holes at 45-degree intervals in each link to house the torsion spring. The rationale behind the eight equally spaced holes was to provide versatility in controlling the spring's stiffness by adjusting its placement within different holes. This strategic design allows us to modulate the joint's flexibility and adaptability according to varying operational requirements.

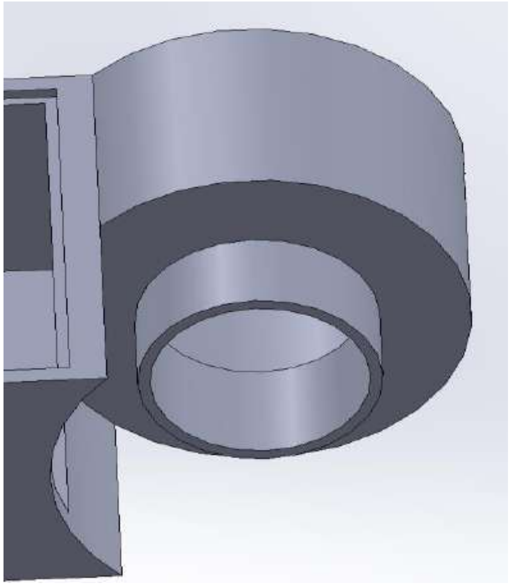

Figure 3.4 link features an extended part

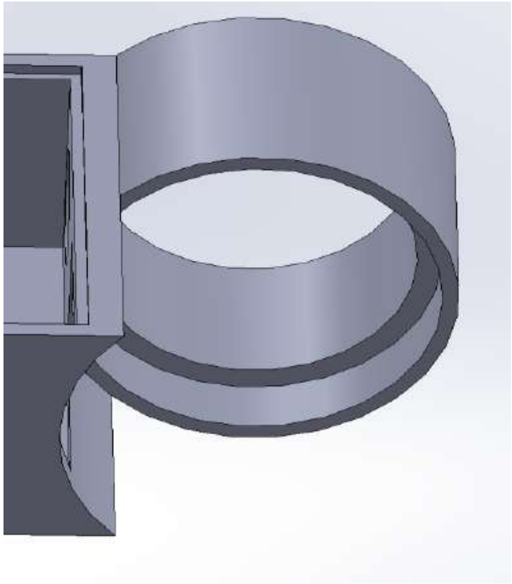

Figure 3.5 Link accommodates the Extended part

3.4 3D Solid Works Design

In our multilink robot design, we've crafted two identical links, each measuring 160mm in length and 50mm in width, as illustrated in below figures 3.6, aligned with considerations for accommodating the DC motor size. These links are engineered to enable potential extensions, featuring one side designed for future expansion, as illustrated in below figure 3.7.

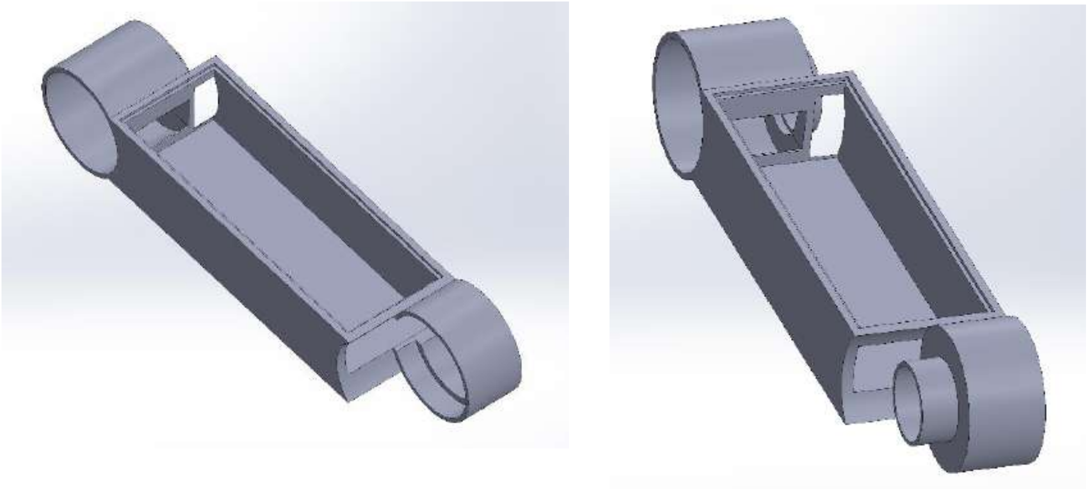

Figure 3.6 Two identical links, each measuring 160mm in length and 50mm in width

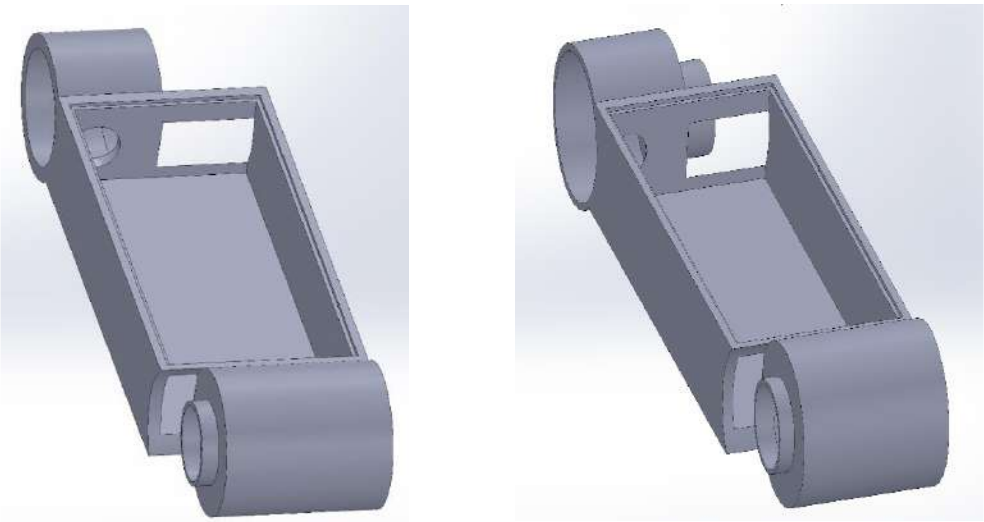

Figure 3.7 Links featuring one side designed for future expansion

The joint formation between the links is purposefully crafted—one link possesses an extension, while the other provides the space or hole to accommodate this extension. To facilitate smooth rotation without friction, circular spaces for bearings have been integrated into the link with the accommodating space, as illustrated in below figures 3.8 and 3.9.

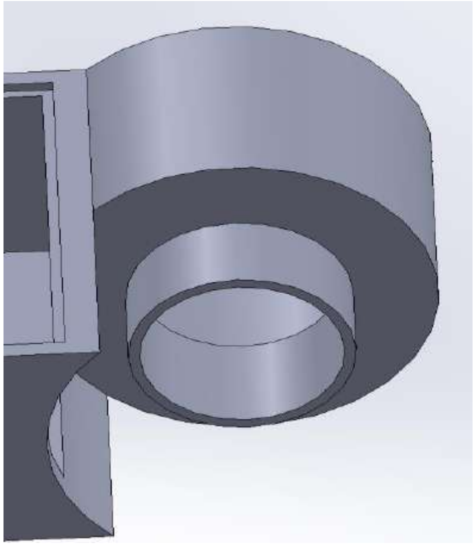

Figure 3.8 link features an extended part

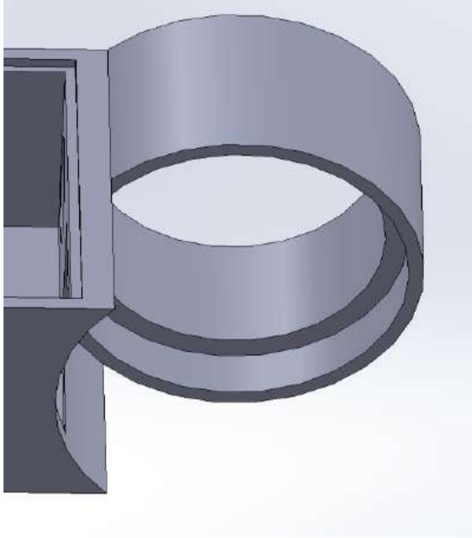

Figure 3.9 Link accommodates the Extended part

The inclusion of bearings between the links ensures seamless rotation, essential for our revolute joint configuration. Additionally, we've incorporated eight equally spaced holes at 45-degree intervals within the joint, intended to house the torsion spring. This design choice allows for altering the spring's stiffness by adjusting its position among these holes, effectively shaping the robot's articulation angles based on specific operational needs.

Moreover, spaces have been meticulously designed within each link to house the bearings, contributing to the shaft/axle smooth operation and stability, as illustrated in below figure 3.10. This detailed 3D SolidWorks design ensures both functionality and adaptability, addressing the robot's dynamic articulation requirements.

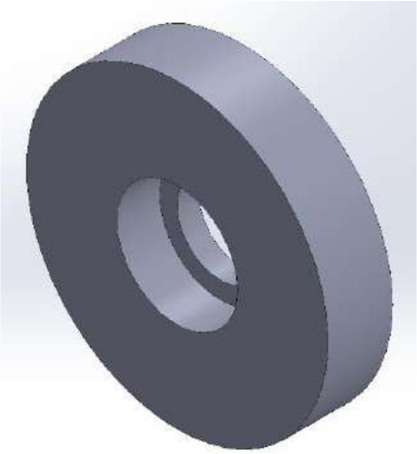

Figure 3.10 Part designed for each side of link to house the bearings

Additionally, we incorporated an extension holder component as illustrated in figure 3.11, designed to temporarily occupy the extension space. When expanding the robot in the future, this holder will be replaced by the new extended link. The term “extension holder” refers not to its role in holding the extended link but rather to its function in maintaining the extension space until the future link extension.

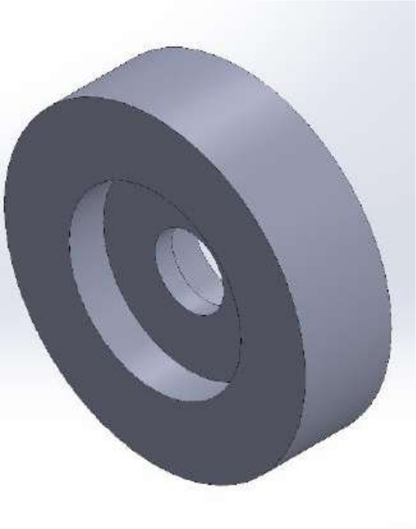

Figure 3.11 extension holder designed to temporarily occupy the extension space

To complete the link structure, we designed covers matching the dimensions of the link housings, serving to enclose and protect the internal components, as illustrated in figure 3.12.

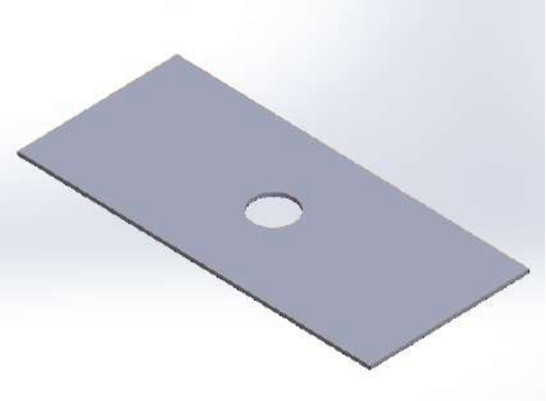

Figure 3.12 Cover matching the dimensions of the link housings

Moreover, a motor holder was engineered to secure the motor in place, ensuring its stability during task execution and maintaining the assembly with gears, as illustrated in figure 3.13.

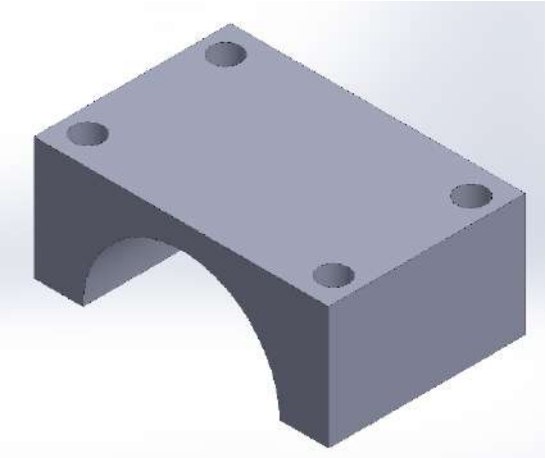

Figure 3.13 Motor holder was engineered to secure the motor in place

3.4.1 3D model Assembly

The assembly of our pipeline inspection robot's 3D model involved a meticulous process aimed at ensuring structural integrity and operational efficiency. The assembly primarily revolved around integrating the various components and subsystems designed to work seamlessly in unison.

The core assembly comprised the articulation mechanism, incorporating the two identical links, each measuring 160mm in length and 50mm in width. These links, designed for potential future expansions, featured an extended part in one and a corresponding space in the other, facilitating smooth rotation aided by precision-fitted bearings.

Integral to this assembly were components such as the motor, bevel gears shaft, and bearings meticulously positioned within the link housings. These components played a crucial role in ensuring the efficient transmission of motion and torque essential for the robot's maneuverability.

The joint mechanism, a pivotal element in the assembly, showcased the careful placement of eight equidistant holes, strategically set at 45-degree intervals. These holes served as mounting points for the torsion spring, allowing articulation control and adaptability.

Auxiliary components like the extension holder, covers matching the link housings, and the motor holder were seamlessly integrated into the assembly, ensuring stability, protection, and functionality.

The 3D model assembly process encompassed meticulous attention to detail, ensuring each component's precise placement and alignment. The final assembly stands as a testament to the integration of innovative design and engineering, poised to deliver exceptional performance in pipeline inspection and exploration tasks.

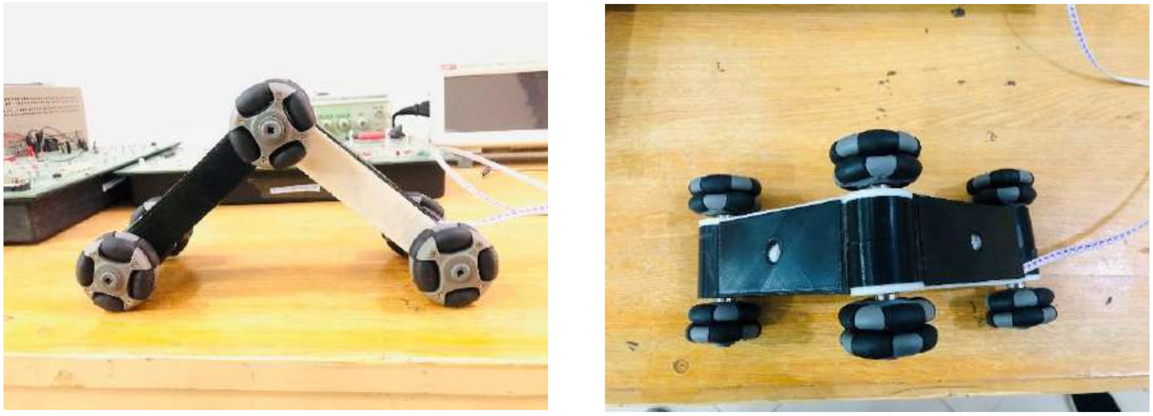

Figure 3.14 Assembled robot

3.5 Electronics Components

Dual Axis XY Analog Joystick Module

The dual-axis XY analog joystick module is an input device that allows manual control of the robot's movement. It consists of two potentiometers, one for each axis (X and Y), and is typically designed as a joystick that can be moved in different directions.

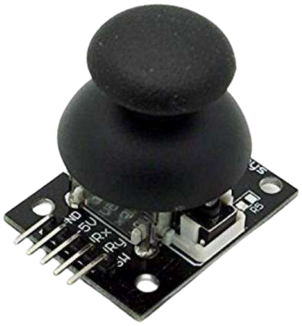

Figure 3.15: Dual Axis XY Analog Joystick Module

Working

As the user moves the joystick in the X and Y directions, the potentiometers measure the analog voltage values corresponding to the joystick's position. These voltage signals are then sent to the Arduino Uno for processing. By interpreting these analog values, the Arduino can determine the desired direction and speed of movement for the robot's wheels.

Arduino Uno

The Arduino Uno is a microcontroller board that serves as the brains of our robot. It is responsible for processing input signals, making decisions, and controlling the L298N motor driver circuit to drive the robot's motors.

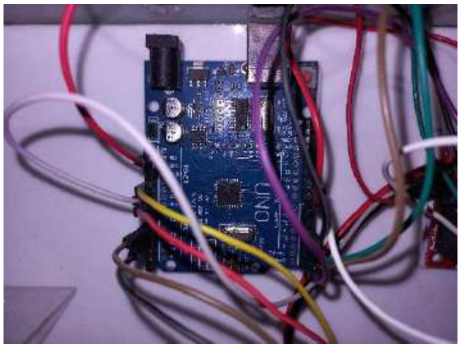

Figure 3.16: Arduino Uno board

Working

The Arduino Uno receives the analog voltage signals from the joystick module and processes them through its analog-to-digital converter (ADC) pins. It translates these signals into specific motor control commands, which are then sent to the L298N motor driver circuit. The Arduino Uno's code defines the logic and behavior of the robot based on user inputs.

L298N Motor Driver Circuit

The L298N motor driver circuit is a crucial component for controlling the robot's motors. It allows the Arduino to provide power and direction control to the motors, enabling precise movement.

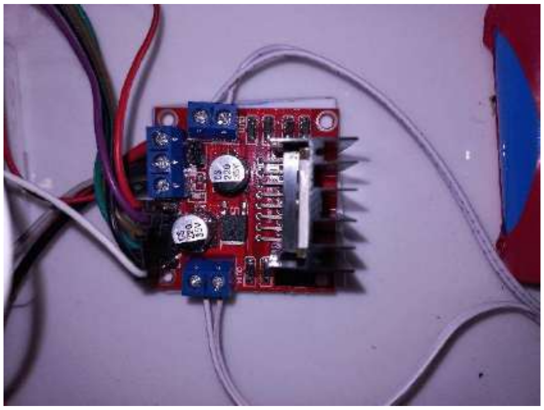

Figure 3.17 L298N Motor Driver Circuit

Working

The L298N motor driver circuit takes input from the Arduino Uno and manages the power supplied to the robot's motors. It can control the direction (forward, backward) and speed (by PWM, Pulse Width Modulation) of the motors. The L298N effectively translates the digital signals from the Arduino into physical movements of the robot by varying the voltage and current supplied to the motors.

3.6 Circuit Diagram

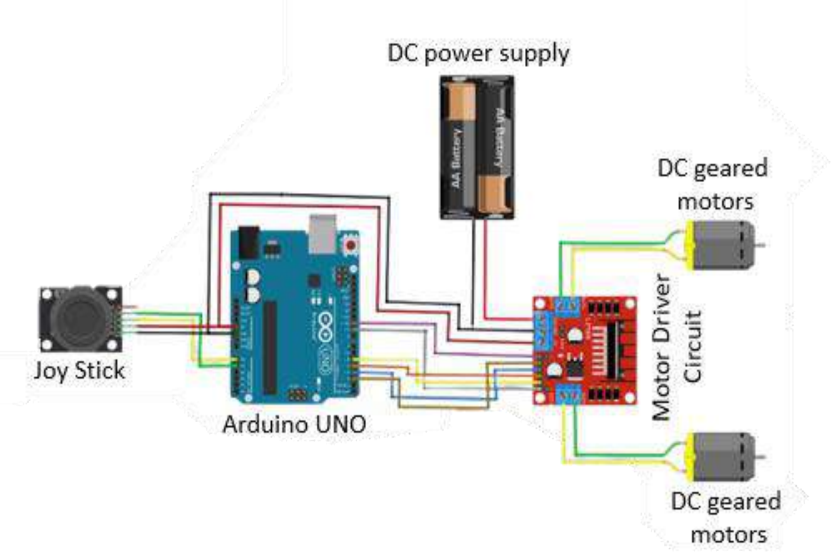

Figure 3.18 Circuit Diagram

3.7 Pseudocode Code

This pseudocode captures the logic and flow of our code using plain language, making it more understandable without focusing on specific programming syntax.

```
// define Motor A and Motor B connections
motorAPin1 = 2
motorAPin2 = 3
enableAPin = 9
motorBPin1 = 4
motorBPin2 = 5
enableBPin = 10

// define Joystick connections
joyXPin = A0
joyYPin = A1

// Setup the pins
Set motorAPin1 as an OUTPUT
Set motorAPin2 as an OUTPUT
Set enableAPin as an OUTPUT
Set motorBPin1 as an OUTPUT
Set motorBPin2 as an OUTPUT
Set enableBPin as an OUTPUT
Set joyXPin as an INPUT
Set joyYPin as an INPUT

// Main loop
While true:
   // Read joystick values
   joyXValue = analogRead(joyXPin)
   joyYValue = analogRead(joyYPin)

  // Map joystick values to motor speeds
   motorASpeed = map(joyYValue, 0, 1023, -255, 255)
   motorBSpeed = map(joyYValue, 0, 1023, -255, 255)

 // Map joystick values to direction control
   if joyYValue > 512:
      motorADirection = 1  // 1 for clockwise
      motorBDirection = 1  // 1 for clockwise
   else:
      motorADirection = -1  // -1 for anticlockwise
      motorBDirection = -1  // -1 for anticlockwise
```

```
  // Control motor direction
  if motorADirection == 1:
    Set motorAPin1 to HIGH
    Set motorAPin2 to LOW
  else:
    Set motorAPin1 to LOW
    Set motorAPin2 to HIGH

  if motorBDirection == 1:
    Set motorBPin1 to HIGH
    Set motorBPin2 to LOW
  else:
    Set motorBPin1 to LOW
    Set motorBPin2 to HIGH

// Set motor speeds
  Set enableAPin to the absolute value of motorASpeed
  Set enableBPin to the absolute value of motorBSpeed
```

Chapter 04
Kinematic Constraints and Experiments

The aim of this chapter is to present the experimental work carried out in order to verify the theoretical work done on the prototype described in the previous chapters. This helps to prove that the robot behaves as calculated and allows the real-world practical limitations of the robot to be observed and quantified.

4.1 Kinematic Constraints

The multilink-articulated wheeled robot was assumed to be a redundant manipulator as it shared a basic structural similarity [51]. Figure 4.1 represents a kinematic model of a nonfixed base 2-link manipulator. L_i , L_{gi} , θ_i , $p_i = [x_i\ y_i]^T$ and $p_{gi} = [x_{gi}\ y_{gi}]^T$ are parameters of the i-th link, which denote the link length, length from the former joint to the center of gravity (COG), relative angle of the link, position vector of the joint, and position vector of the COG, respectively. Normally, a 2-link manipulator has two degrees of freedom. However, the base of the robot is not fixed (it floats in the space). In addition to the 2-DOF, other translational motions of the base in x and y directions involve the motion of the whole robot as a variable of p_0.

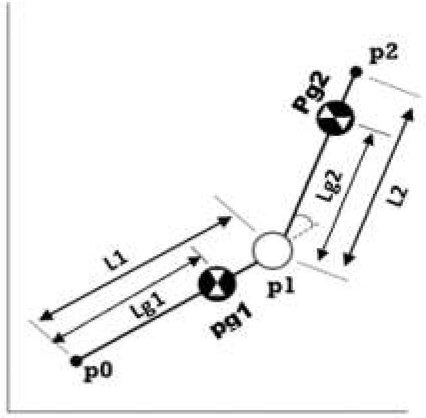

Figure 4.1 Kinematics model of a non-fixed base 2-link snake robot

4.1.1 Constraint in a straight pipe

The multilink-articulated wheeled robot could passively adapt to the bent pipe owing of its spring joints. However, spring torque decreases while the joint is contracting. As the robot could slip due to the low clamping force, especially in vertical situations, this situation is harder than that of the horizontal situations. The clamping force directly relates to the spring torque that depends on the stiffness of the spring and the rotational angle from its natural angle. The amount by which the angle of the joints should shrink in the straight pipe can be geometrically derived as shown in figure 4.2. H_w, and H_j denote the restricted space of the straight pipe, For example, Omni wheels move within the space H_w as depicted in Figure 4.2. Accordingly, the axes of the omni-wheels are restricted within H_j. where W denotes the width between a pair of the omni wheels.

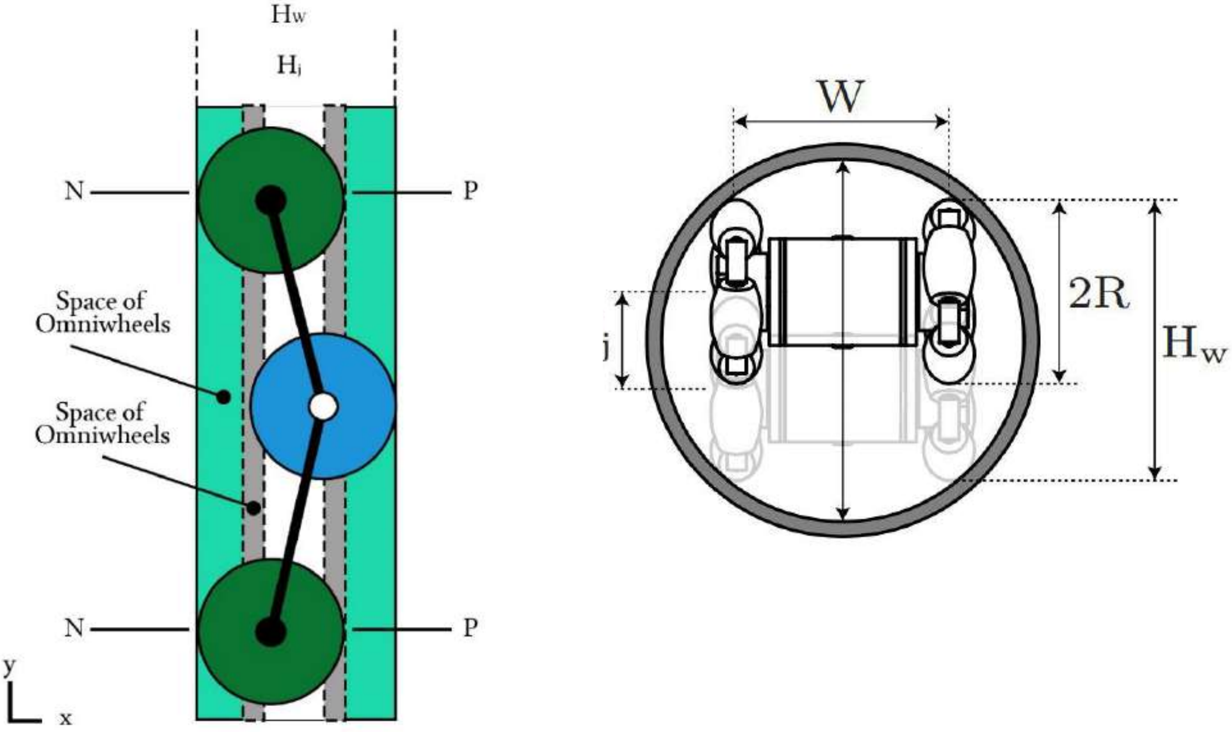

Figure 4.2 Restricted space and external forces in a straight pipe

4.2 Experimental Setup

4.2.1 Experimental Goals

For the experimental phase, four distinct setups are employed, each representing varying orientations of straight pipes concerning the Earth's surface, as illustrated in the accompanying figure. The objectives for these setups are defined as follows:

Setup 1: Horizontal Straight pipe (o degrees from earth's surface)

The primary goal is to navigate the robot within a horizontal straight pipe, maintaining a zero-degree angle concerning the Earth's surface. This setup serves as the baseline scenario for the robot's movement and maneuverability.

Setup 2: Straight pipe at 30 degrees from earth's surface

The objective here is to drive the robot within a straight pipe inclined at a 30-degree angle from the Earth's surface. This setup aims to test the robot's adaptability and traversal capabilities in moderately inclined pipelines.

Setup 3: Straight pipe at 60 degrees from earth's surface

This setup involves maneuvering the robot within a straight pipe inclined at a more challenging 60-degree angle from the Earth's surface. The goal is to assess the robot's performance and stability in navigating steeper inclinations.

Setup 4: Vertical straight pipe (90 degrees from earth's surface)

The final objective revolves around driving the robot within a vertically positioned straight pipe, presenting a 90-degree angle concerning the Earth's surface. This setup evaluates the robot's ability to operate effectively in a vertical orientation, representing extreme pipeline configurations.

These experimental setups aim to comprehensively evaluate the robot's capabilities across varying pipe inclinations, ranging from horizontal to vertical orientations. The outcomes derived from these experiments will provide insights into the robot's adaptability, maneuvering efficiency, and operational limitations within diverse pipeline environments.

4.2.2 Materials and Dimensions

For the experimental trials, vinyl chloride (PVC) pipes serve as the primary material for creating the simulated pipeline environments. These PVC pipes adhere to the following specifications:

Material type: Vinyl Chloride (PVC)

Pipe Diameter: 5 inches

Pipe length: 3 feet

The choice of 5-inch diameter PVC pipes with a length of 3 feet is deliberate, aiming to replicate standard pipeline dimensions commonly encountered in various industrial and infrastructural settings. These dimensions ensure a realistic representation of the pipeline environments encountered during inspection and exploration tasks.

The PVC pipes' material composition offers durability and ease of manipulation for experimental setups while providing a suitable environment for testing the robot's maneuverability and navigation capabilities within confined spaces.

The selection of these specific dimensions aligns with industry standards and allows for comprehensive experimentation to evaluate the robot's performance across various orientations and configurations of pipes commonly found in real-world applications.

4.2.3 Protocols and Experimental Results

4.2.3.1 Experiment 1: Driving forward and backward in horizontal straight pipe

Conducting multiple experiments within straight pipes across varying inclinations, the robot showcased remarkable adaptability, overcoming friction and slippage while moving smoothly through different pipe orientations. These experiments yielded resounding success, affirming the robot's proficiency in navigating diverse pipe configurations.

Figure 4.3 Driving robot forward and backward in horizontal straight pipe

4.2.3.2 Experiment 2: Driving up and down in straight pipe inclined at 30 degrees from the earth surface.

In the inclined 30-degree pipes, the robot successfully mitigated friction and slippage, executing movements smoothly while ascending and descending. This highlighted the robot's robust design and torque capabilities, notably demonstrating its suitability for varied pipe inclinations.

Figure 4.4 Driving up and down in straight pipe inclined at 30 degrees from the earth surface.

4.2.3.3 Experiment 3: Driving up and down in straight pipe inclined at 60 degrees from the earth surface.

Further trials in the steeper 60-degree inclined pipes affirmed the robot's ability to overcome challenges associated with increased inclines. The robot adeptly maneuvered, indicating sufficient torque from the DC geared motors and the spring mechanism to adapt and navigate effectively.

Figure 4.5 Driving up and down in straight pipe inclined at 60 degrees from the earth surface.

4.2.3.4 Experiment 4: Driving up and down in vertical straight pipe inclined at 90 degrees from the earth surface

The most challenging experiment involved navigating within vertical pipes at a 90-degree inclination from the Earth's surface. Remarkably, the robot seamlessly moved within these vertical pipes, showcasing exceptional torque capabilities from both the DC geared motors and the spring mechanism. These successful trials underscored the robot's adaptability even in the most demanding pipe configurations.

Figure 4.6 Driving up and down in vertical straight pipe inclined at 90 degrees from the earth surface

Collectively, these experiments emphasized the robustness of the robot's DC geared motors, demonstrating ample torque to overcome friction and slippage across varying inclinations. Additionally, the spring mechanism exhibited sufficient torque to adapt to vertical 90-degree pipes, enabling effective navigation.

The findings from these experiments highlight the potential of multilinked articulated snake-type inspection robots in streamlining pipeline inspection tasks. Their superior adaptability and torque capabilities position them as viable solutions for navigating and inspecting pipes more efficiently than other robotic counterparts, particularly in challenging and diverse pipeline environments.

Chapter 5

In this concluding chapter, we navigate through the achievements of developing a pipeline inspection robot. We reflect on its successful design, testing, and execution, while also peering into potential advancements that could revolutionize pipeline inspection methodologies. This chapter encapsulates the culmination of our efforts and paves the way for future enhancements in pipeline inspection robotics.

5.1 Summary

This thesis embarked on an exploration of multilink articulated snake-type robots tailored for pipeline inspection, focusing on their maneuverability, adaptability, and torque capabilities within varying pipe orientations. The series of experiments conducted aimed to evaluate the robot's performance in simulated pipeline environments, yielding significant insights and affirming its potential for practical applications.

The experimental trials showcased the robot's remarkable adaptability across different pipe orientations. From navigating horizontal straight pipes to ascending and descending in inclined pipes up to 90 degrees from the Earth's surface, the robot consistently demonstrated precise movements and efficient traversal capabilities. Its ability to overcome challenges such as friction, slippage, and differing inclines highlighted the robustness of its design and torque mechanisms.

Notably, the DC geared motors exhibited ample torque, enabling the robot’s-controlled movements even in challenging inclinations. Additionally, the spring mechanism showcased its adaptability, effectively aiding the robot in adapting to varying pipe configurations, including vertical orientations.

The successful outcomes of these experiments underscore the potential of multilink articulated snake-type inspection robots in streamlining pipeline inspection tasks. Their superior adaptability, precise maneuvering, and torque capabilities position them as promising solutions for enhancing efficiency and accuracy in pipeline inspection and exploration endeavors.

5.2 Future Work

The current iteration of the pipeline inspection robot lays a solid foundation for future advancements and expansions in its capabilities. Several areas of potential development stand out, presenting opportunities for enhancing its functionality and applicability in pipeline inspection tasks.

Adaptation for Bend Pipes

The extendable design of the robot lays the groundwork for future adaptations to navigate through bend pipes. Implementing mechanisms or modules allowing the robot to maneuver through curved or serpentine pipelines would significantly broaden its scope for inspecting complex pipe geometries. Exploring flexible or articulated segments could enable the robot to negotiate bends while maintaining its effectiveness in data collection and inspection.

Integration of Camera and Sensors

Extending the robot to incorporate camera and sensor modules represents a critical avenue for future development. Equipping the robot with high-resolution cameras and advanced sensors can augment its inspection capabilities. These enhancements would facilitate real-time data collection, enabling the robot to capture detailed images and gather vital information about the pipeline's condition, potential defects, or irregularities.

Enhanced Data Collection and Analysis

Enhancements in data collection methods and analytical capabilities present another promising area for future work. Integration of sophisticated data processing algorithms and artificial intelligence could empower the robot to analyze collected data on-site. This advancement would allow for immediate detection of anomalies, enabling prompt decision-making and facilitating preventive maintenance measures.

Autonomous Navigation and Control

Further developments in autonomous navigation and control mechanisms could significantly enhance the robot's operational efficiency. Implementing advanced control algorithms and machine learning techniques could enable the robot to make autonomous decisions regarding optimal paths, inspection routines, and adaptive responses to varying pipeline conditions.

Material and Component Upgrade

Continuous advancements in materials science could lead to the development of lighter yet more durable components. Integration of such materials into the robot's design would not only enhance its performance but also increase its endurance and longevity in challenging pipeline environments.

In summary, the extendable nature of the robot design offers ample opportunities for future extensions and enhancements. Incorporating capabilities for maneuvering in bend pipes, integrating sophisticated inspection tools, advancing data collection and analysis methods, refining control mechanisms, and leveraging material advancements are key directions that can further elevate the robot's effectiveness in pipeline inspection and exploration.

5.3 Conclusion

The development of a pipeline inspection robot involved meticulous research, strategic decision-making, and innovative engineering solutions aimed at creating an adaptable and efficient inspection tool. The journey commenced with comprehensive research, culminating in the selection of a snake-type robot design and locomotion mechanism, recognized for its suitability in navigating confined pipeline environments.

The deliberative process led to the selection of appropriate actuators and the design of a robust torque and speed transfer mechanism, crucial for facilitating locomotion. Leveraging SolidWorks, a detailed 3D model was meticulously crafted, taking into account the actuators' specifications and ensuring a functional and reliable design.

The translation of the 3D model into tangible parts through 3D printing marked a significant milestone, followed by the intricate assembly of these components into the final robot prototype. Programming the electronic components to orchestrate the robot's movement and integrating them seamlessly with the 3D model constituted a pivotal stage in the project's execution.

The culmination of these endeavors resulted in a fully functional pipeline inspection robot capable of maneuvering through various protocols and pipe orientations. The experiments conducted in different protocols validated the robot's adaptability, torque transmission, and speed control mechanisms.

Throughout this journey, the interdisciplinary collaboration, amalgamation of engineering principles, and innovative problem-solving were instrumental in achieving the project's objectives. The successful execution of this project signifies not only the technological advancements achieved but also the potential for transformative solutions in the field of pipeline inspection and maintenance.

While the current iteration of the robot demonstrates promising capabilities, there remain avenues for future enhancements. Exploring further adaptability for bend pipes, integrating advanced inspection tools, refining control mechanisms for autonomous navigation, and leveraging material advancements stand as potential directions for advancing the robot's capabilities and applicability in diverse pipeline environments.

In conclusion, this project represents a culmination of rigorous research, innovative engineering, and successful execution, laying the groundwork for further advancements in pipeline inspection robotics. The developed robot stands as a testament to the possibilities of technology in revolutionizing pipeline inspection and maintenance methodologies.

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