Simulation Based Analysis of Pipe Cleaning Robot

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***Abstract*—Pipelines majorly transport water, sewage and oil. The accumulation of debris on waterways over long periods of time affects the flow of water and the quality of the water. First, a water system robot is introduced here. It is designed to employ a thin pipe with the diameter of a quarter. The robotic has multi directional movements involving moving forward and backwards in addition to water jet head and a specimen tool for pipe surface contact. It has been specifically developed to work with the pipeline's infrastructure. This piece incorporates a rotating water jet function, and a specially designed piece meant to reach directly into the pipe. Solid works software was used to create a 3D model with Simulink simulating the robot dynamics. The robot that is being developed is expected to lower the cost, man-hours and time in maintaining.**

***Index Terms*—In-pipe robotics, Pipe Cleaning, SolidWorks, Matlab Simulink**

I. Introduction

Pipelines are the key means to supply several important aids, such as water, gas, and oil. Corrosion, cracks, mechanical damage, and dirt deposition due to long time of usage are factors that affect the performance of pipelines. Maintenance, repairing, and cleaning need to be conduct regularly for the pipelines to be functioned properly. In order to reduce the cost and the complexity of this process, robot systems are being used widely. These robot systems need to be optimum when it comes to usage of power and also its mechanical and electrical systems should not be affected by the fluid existence.

Fig. 1. A figure of a pipeline

Cleaning the dirt deposited inside the pipelines is the focus of the project. Sensors are installed along the pipelines in order to locate the positions where the dirt is deposited and it is done via inspecting the flow rate variation through the pipeline. The detected clog location (the coordinates of the sensor locations where the variation of flow rate detected) is given to the robot system as an input where all the input signals and parameters are set according to that coordinate.

According to the given inputs the robot system initiates its motion and cleaning process. This robot system consists of two main mechanisms : motion mechanism and the cleaning mechanism.

II. Literature Review

The development of pipe cleaning robots has gone through various transformations corresponding to unstoppable technology advancement. The early versions of these robots were simple tethered machines controlled by humans. They used brushes to sweep away debris from inside the pipes. More sophisticated mobility solutions became evident as robotics advanced. Robots have used wheels, tracks, and other specialized parts as means of self-mobility through different sizes and shapes of pipes.

The evolution of these robots reached a critical point when they moved from tethered to wireless control systems. In this case, these machines were free from the constraint of physical cables because operators controlled them at a distance thus enhancing operational flexibility. The paradigm on wireless also enabled real-time data transmission whereby operators get immediate feedback on what the robot is doing.

Most of the modern pipe cleaning robots have an array of sensors built into them. Cameras are very important as they provide visual feedback on pipe interior conditions and allow operators to see inside them. Ultrasonic sensors are used to detect any blockage or anomalies by sending high-frequency soundwaves to different objects. Collectively, these sensors improve a robots ability of navigating intricate pipe mazes while simultaneously performing in situ diagnostics.

Additionally, artificial intelligence progress has enabled these robots to make smarter decisions. Therefore, machine learning algorithms may help the robots to modify their cleaning strategies according to different circumstances occurring within the pipes for efficient and effective task completion. With time and the advancing technology, pipe cleaning robots may continue to evolve, becoming more sophisticated and equipped with new capabilities to inspect and maintain complicated network of pipes.

Pipe cleaning robots can be classified into several categories according to their mechanism such as locomotion type, based on structure, sensors used for in-pipe inspection and cleaning method. According to the [3], Pipe cleaning robots can be categorized according to the type of wheels. Those categories are wheels, track/caterpillar, shrew and pig type, snake and legged type and inchworm type.

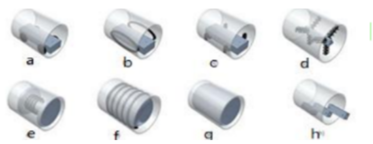

Fig. 2. the pipe-cleaning robot locomotion type

Letter	Type
a	Wheel type
b	Track / caterpillar type
c	Leg type
d	Wall-press type
e	Inchworm type
f	Screw type
g	Pig type
h	Snake type

TABLE I

The wheeled pipe robots have simple designs, but they move only in horizontal pipes. Despite this, these robots fail to offer enough support to their structure as they move within the pipeline. Wider wheels' tracks can be employed to enhance support and help offer stability to the robot's body as it transverses the pipeline. [5]

Caterpillar-type pipe robots offer better traction inside the pipe compared to regular wheeled robots. Additionally, they are versatile and can work well in pipes of different sizes. [5]

The wall-pressed-type in-pipe function between pipe walls are useful for movement in vertical pipes. These robots have the ability to deliver large enough forces for smooth moving along the vertical pipes not letting off. On the other hand, the inchworm-type robots are easy to control and direct the robot to interact with the different components of infrastructure.

Firstly, they use a vibration source that is within the pipe. Push against the wall of the tube as a passive device linked to the driving force. These things are just of few components. The operation of these robots is done by a linear actuation of their motion together with a retraction and an extension of the limbs. Straight and elbow fittings so that they may move in a straight line. Inchworm robots march unlike inchworms. In motion, they are relatively slower than wheeled robots that tend to be continuous movements. [3]

The structures can also be used to differentiate locomotion type and pipe cleaning robot. According to [3], There are four types of in-pipe robots based on structures: plane form, single plane, arms 180 degrees, triple plane form, arms 120 degrees, quadruple plane form, arms 90 degrees, and hexagonal plane form. The structures are depicted in figure 3.

Fig. 3. In-pipe robotic structure forms

Due to the cleaning method pipe cleaning robots can be divided in to two groups. They are tools based and the pressure-based. Those types are shown in the figure provided in below.

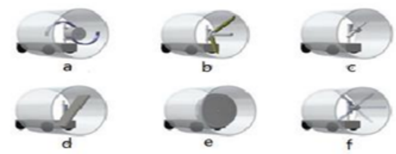

Fig. 4. Caption

a	Impact abrasion with flails
b	Umbrella type
c	Commercial -vehicle type
d	Cutter cleaner arm
e	Disk cleaner disk
f	Pressure-based

TABLE II

Depending on the type of sensors used, pipe cleaning robots can be classified into 6 types. The robot comes equipped with various sensors specifically for inspection purposes. These tasks involve identifying corrosion, obstructions, imperfections like flaws and cracks, as well as tracing and locating within the pipe. The sensors employed for these tasks are diverse:

1) Ultrasonic sensor
2) Magnetic sensor
3) Infrared sensor
4) Vision sensor (camera)
5) Tactile sensor
6) Light amplification by stimulated emission of radiation (LASER)

Most of these sensors operate as range sensors, primarily measuring the distance between a point and the objects within the pipe. [6]

III. Problem Statement

In modern industrial and municipal infrastructure, the maintenance of pipelines is an indispensable yet challenging task. The essential pathways carry freshwater from public services and into buildings using materials such as copper, ductile or cast iron and PVC. The accumulation of debris, sedimentation, and the growth of biological fouling within pipes pose significant operational and environmental concerns. Traditional methods of pipe cleaning often involve manual labor or intrusive procedures that can be costly, time-consuming, and occasionally hazardous. However, the advent of pipe cleaning robots has revolutionized this field by offering an innovative, efficient, and non-disruptive solution.

According to [1] and [2] ,using in-pipe robots as an effective yet economical solution to overcome these problems. Maintenance and cleaning of such sites can be easily addressed through the use of these robots avoiding the complexities surrounding human intervention.

Pipe cleaning robots represent a cutting-edge technology designed to autonomously navigate through complex pipeline networks, performing cleaning and inspection tasks with precision. Equipped with advanced sensors, locomotive mechanisms, and cleaning tools, these robots offer a proactive approach to maintaining pipeline integrity while minimizing downtime and operational disturbances. Their ability to adapt to various pipe diameters, materials, and environmental conditions makes them versatile assets in diverse industries, including wastewater management, oil and gas, and utilities.

This research paper aims to delve into the intricacies of pipe cleaning robots, exploring their design, functionality, operational capabilities, and the impact they have on enhancing the efficiency and sustainability of pipeline maintenance. Through an in-depth analysis of their technological advancements, operational benefits, and future prospects, this paper seeks to highlight the pivotal role that pipe cleaning robots play in reshaping the landscape of pipeline maintenance and management.

IV. System Overview

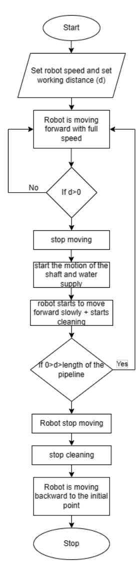

Fig. 5. Flow chart for the process

The pipe cleaning robot is composed of three components: a forward-backward moving unit, a rotating water jet, and an internally rotating brush. The forward-backward module enables the robot's motion within the pipeline. First, the robot uses its sensor system to identify the position of the pipe where the dirt is located. It is determined by the change in the speed of the water flowing in the pipe Upon detecting dirt in the pipe, the robot halts its movement, triggering simultaneous rotation of the shaft, water jet, and internal brush. This coordinated action initiates the cleaning process as the water jet dispenses water and the rotating brush cleans the pipe's interior. Subsequently, upon completion of the cleaning cycle, the shaft stops rotating, and concurrently, the water jet and internal brush cease their rotation. As a result, once the initial dirt spot is cleared, the robot accelerates forward at a significant speed until it identifies another dirt location within the pipeline.

V. System Design

Each component underwent modeling using SolidWorks software whereby it underwent the necessary dimensions to ensure it met the specific cleaning robot requirements. In order for the robot to be optimally designed, it was dimensioned for the same purpose. It consists of three primary modules: Water Jet, Rotating Brush, and Forward – Backward Moving Module. Thereafter, a bottom-up technique was used to put together all the components that led to the final design. Figure 6 demonstrates the final robot which can be seen in two settings; open and closed. There is a table describing the parts which has a corresponding picture of the cleaning robot.

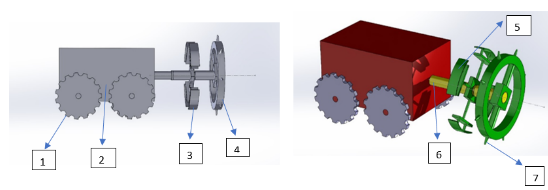

Fig. 6. cleaning robot design and with its part

Part No	Name
1	Wheel
2	Body
3	Rotating brush
4	Rotating water jet
5	The surface that holds the brush
6	Shaft
7	Water nozzle

TABLE III
PARTS DESCRIPTION

A. Wheels

The working location of pipe cleaning robot is inside of water pipes or sewer pipes. Due to its wetness and slippery nature, it is a bit difficult to move in it. Therefore, the wheels of the robot do significant work. Pipe cleaning robot can be categorized according to the type of wheels. Those categories are wheels, track/caterpillar, shrew and pig type, snake and legged type and inchworm type. The Wheel robot provides significant advantages that other types such as energy efficiency, the possibility of miniaturization, control techniques, they maintain contact between the moving wheels and the pipe wall by using their weight, these robots are able to traverse pipes with infinite pipe diameters and pipelines that are horizontal or slightly incline can be traversed by them. [3]

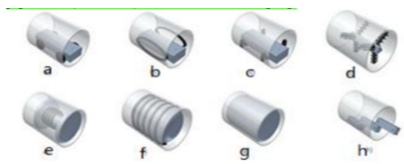

Fig. 7. Types of Wheels

Due to those reasons, the wheel type was used for the Pipe cleaning robot. Wheels designed to minimize friction were used.

The wheel is a 130mm Polyurethane wheel, fashioned with a gear-like profile, minimizes friction in our pipe cleaning robot. Here, one motor is installed for the two rear wheels and one motor for the two front wheels. This design innovation optimizes contact points, enhancing maneuverability within pipes. The gear-inspired structure reduces resistance, ensuring efficient traversal and debris removal. The wheel's consistent size ensures stability, while its Polyurethane composition promises durability and chemical resistance, crucial for sustained performance in diverse pipe environments.

B. Body

Stainless steel is used to make the body of the pipe cleaning robot. The body is 170 millimeters wide and 270 millimeters long. It has a height of 150 millimeters.

- Reason for use the stainless steel for body of pipe cleaning robot
  According to [4], Stainless steel is an alloy composed of iron, chromium, and other elements, providing excellent corrosion resistance and durability. It exhibits high strength, making it suitable for robust applications. Its corrosion resistance ensures longevity, crucial for robots operating in potentially corrosive pipe environments. Stainless steel is easy to clean and maintain, essential for equipment operating in sanitation-sensitive areas. It can be fabricated into various shapes and sizes, allowing for the customization of robot body components to fit different pipe dimensions. Stainless steel can withstand a wide range of temperatures, enabling the robot to operate in diverse pipe conditions.

C. Rotating brush

Stainless steel serves as the material for the rotating supporter in the pipe cleaning robot, while Nylon is selected as the brushing material. Nylon's attributes include toughness, flexibility, and resistance to abrasion. It's versatile, allowing for varied shapes and sizes, catering to different pipe diameters. Moreover, Nylon withstands exposure to diverse chemicals commonly present in pipes without swift degradation. Its operational range across a wide span of temperatures makes Nylon brushes adaptable to varying pipe environments.

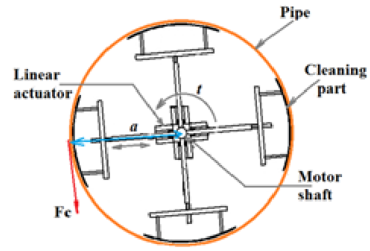

Fig. 8. Rotating Brush

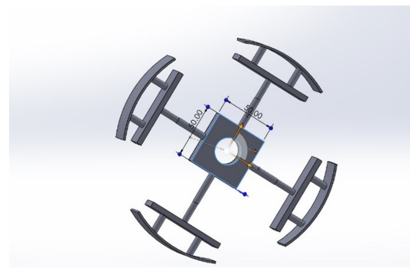

Fig. 9. Rotating Brush Designed using SolidWorks

D. Rotating water jet

The rotating water jet consists of a support frame and a water nozzle. Its feed frame has a diameter of 200 millimeters. It is connected to a water supply through a pipe, which is directly connected to the shaft. The water nozzle is used to spray water and it has 25 millimeter height. It is expected to remove the dirt stuck in the pipe. It can rotate around the axis of the shaft. The motor connected to the shaft gives the necessary power to the rotation. Stainless steel is also used for its construction. Its resistance to corrosion and durability are important here.

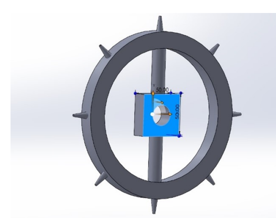

Fig. 10. Water Jet Designed using SolidWorks

VI. MATLAB MODELS AND SIMULATION RESULTS

A. Clog Detection

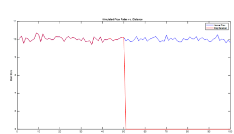

Fig. 11. Plot for the Clog Detection Process

Detecting the clog location is the first task to be done in order to initiate the mechanism of the entire robot system. Figure 13 showcase the clog detected location with respective flow rate.

B. Simulink Model for the Robot System

After designing the robot model on SolidWorks, the 3D design was transfered to the Simulink environment as Simulink blocks to simulate robot motion and dynamics. Figure 12 illustrates the created robot system Simulink model.

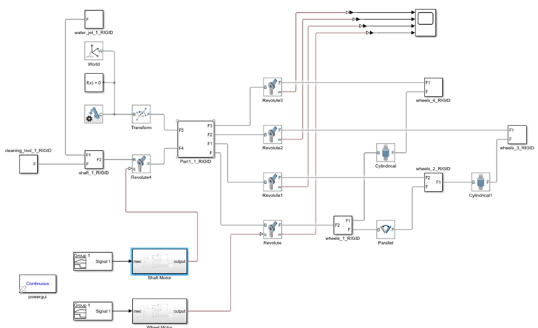

Fig. 12. Simulink Blocks

C. Motor Model

DC motor model is designed and added to the robot system as a subsystem, in order to power-up the shaft and four wheels of the robot system. Figure 13 shows the simulink model of the designed DC motor.

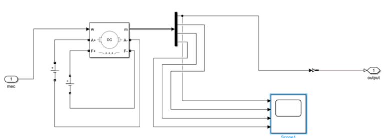

Fig. 13. Simulink model for the DC motor

D. Input Signals

Input signals for the shaft motor and wheel motors are included below.

1) Input Signal for the Shaft Motor: Figure 14 represents the input signal for the shaft motor. It does not have any movement until it reaches the location of dirt, which was detected by the sensors of the robot previously, using the flow rate. Once it reaches the detected location, it starts the rotational motion at a constant speed until the cleaning process is completed.

2) Input Signal for the Wheel Motors: Figure 15 illustrates the input signal for the wheel motors. All four wheels are given the same input signal as we our robot is designed for straight pipelines. From the entrance of the pipe to the location of dirt, the wheels spin at a constant speed. After reaching the clogged location, they stay still for a second and restart spinning in a constant but a lower speed, according to the amount of dirt, in order make the cleaning process a success.

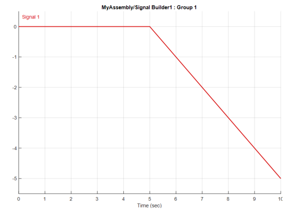

Fig. 14. Shaft Motor Input

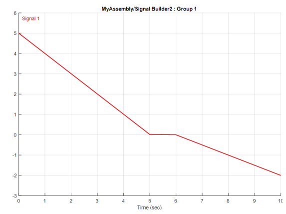

Fig. 15. Wheel Motor Input

E. Output Signals

1) Speed variation of the shaft: The motor shaft is designed to initiate rotation once the robot has reached the clogged location. There after it continues to rotate in a constant speed. Figure 16 represents the speed of the shaft during the cleaning process which is a constant, where the speed is given as an input to the system.

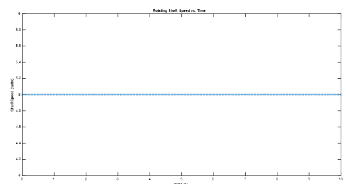

Fig. 16. Shaft Speed Variation

2) Behaviour of the wheels: Figure 17 is to make sure that all four wheels of the robot are following the same mechanism to the given input signal. As it moves into a straight pipeline, all four wheels need to behave in the same manner to complete the locomotion.

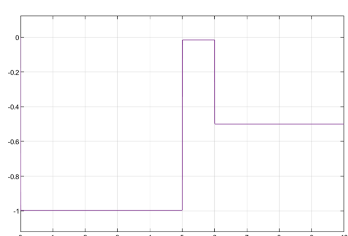

Fig. 17. Behaviour observance

VII. Conclusion

A new robot system for pipe cleaning has been designed for horizontal pipelines. Further, translational and rotational mechanisms of the system is tested using Matlab and Simulink blocks. The robot exhibits commendable cleaning efficacy, automation capabilities, versatile application, and cost-effectiveness. Anticipated benefits include improved indoor water quality, leading to enhanced living and health standards. As for the future developments, enhancing the navigation ability in vertical pipelines, installing a camera system for further inspections and, ability to proceed in active pipelines could be researched.

VIII. Individual Contribution

Gunawardana G. T. S. (210197U) - Matlab code for the clog detection and motor shaft, Design of DC motor in Simulink.

Herath H. H. G. G. (210213T) - 3D model designing of the robot system in SolidWorks and importing to Simulink.

Hettiarachchi S. L. (210221P) - Integrating motor subsystems with input signals, and finalizing Simulink block.

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