

Belted Pipe Robot: A robot for internal inspection of 2-inch pipes

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Abstract—The belted pipe robot is intended for travel through pipe networks. This model was designed to be self-everting, as it propels itself through pipes by two belts that push against opposite sides of the pipe. The prototype has the advantage of being compact (with a height and width under 2 inches) and only using one motor. It is intended for travel within the 2 inch subsections of pipe systems, the diameter of pipes that run between main pipes and individual buildings, and would be transported to these smaller pipes by a larger robot. The belted robot is made primarily from a small motor, seven gears, a differential, two pulleys, two timing belts, and a wheel. Through a series of gears, the DC motor rotates a differential, which turns the pair of pulleys in opposite directions. These pulleys rotate the two belts against the walls of the pipe, moving the entire robot forward or backward. The robot uses rigid belts that are able to gain traction against PVC and metal pipes such that it is successfully able to travel through pipes with a 2 inch diameter. In order to analyze the performance of the prototype, calculations were made of the theoretical and experimental speed of the robot in the straight pipe and 90 degree elbow. Experimental validation of the robot's performance is presented in horizontal pipes and elbows, which make up the majority of 2 inch diameter pipe systems.

Index Terms—two-inch pipe robot, field robots, in-pipe inspection, mechanism design of mobile robots

I. INTRODUCTION

In the present age, pipelines are indispensable for moving water, gas, and other resources. Therefore, it is essential to regularly inspect and repair these aging pipelines to detect any damage or defects before they cause leaks and explosions, which otherwise could cause financial damage and endanger lives. However, inspecting pipelines is often challenging, especially in hard-to-access locations like underground, underwater, or at high altitudes.

A. Belted Pipe Robot

The belted pipe robot was constructed in order to travel through pipes in order to locate cracks and other damage within pipe networks. Since 2 inch pipes are typically offshoots of larger 4 to 6 inch water or gas mains, the robot would be deployed by a larger robot intended for travel within pipe mains. While the larger main pipelines often have complicated junctions including T-joints, 2 inch diameter pipes typically consist of primarily straight and curved sections. The self-everting belt design has the advantage of using less parts than a more traditional drivetrain in which the robot moves using wheels. The robot also has the advantage of having a single motor. This allows the robot to have

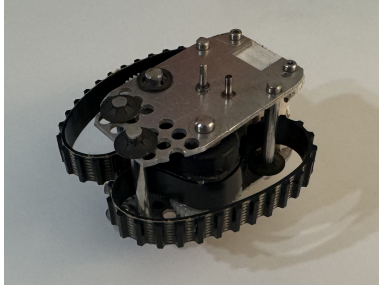


Fig. 1. The belted pipe robot prototype

a more compact design, giving it the ability to travel through 2 inch pipes and the potential to be scaled down such that it could be used in 1 inch diameter pipes. The main intended purpose is to attach an endoscope or humidity sensor to the robot and use it to inspect 2 inch diameter utility pipes in order to determine the location or cracks or other damage.

B. Classification of In-pipe Robots

In-pipe robots have different designs to move them through pipelines. Mills et al. [1] analyzed robots from 1987 to 2015 which used wheels, caterpillar tracks, arms, legs, and telescoping mechanisms to propel themselves through pipes. In their review of 234 robots, only 18 % of the robots employed a single type of propulsion mechanism. The most common method of generating in-pipe traction was wall-pressing, accounting for 44% of robotics research. Of those, there have been a few pipe robots similar in design to the robot presented in this paper, each with self-everting designs. The everting toroidal robot, also known as the sliding membrane locomotion robot, such as the one designed by Perez and Coad [2] involves a plastic tube filled with air that moves forward by constantly everting and inverting simultaneously. Similar to the everting toroidal robot, Eken et. al [3] present a design for a skin eversion robot which is able to dig through a granular environment such as sand, as seen in Fig. 2. The nature of a self-everting design reduces drag within the medium and reduces slippage. Commonly in both everting toroidal and skin eversion robots, 2 to 3 motors rotate several

guide rollers so that the inside of the plastic sliding membrane continuously turns inside out, allowing the entire robot to move forward. While toroidal robots are able to navigate pipes and sand successfully, this design has the drawback of requiring multiple motors and other large components. Due to their larger size, most toroidal robots have only been able to travel through 4 to 6 inch diameter pipes.

Rashid et. al [4] give a review of additional in-pipe inspection robots. The authors conclude that wheeled in-pipe robots are viable for pipe inspection, but require additional research determining how to transition between straight and curved sections of pipe networks due to the differing characteristics of the two sections. Rashid et. al also explain that screw-drive or helical type designs are viable, however these designs are often large due to the number of components required. While these various designs each have their own advantages and disadvantages, a challenge for all pipe robot prototypes is operating in a 2 inch diameter pipe. Nagase et. al [5] introduce a pipe robot which uses six crawler belts in order to propel itself through pipe networks. The design uses a single motor which rotates a worm, turning all six crawler belts simultaneously. The robot is 92 mm long, but was able to navigate 3 inch diameter pipe systems. A potential downside to this design is that the large number of components required could make downsizing the design impractical.

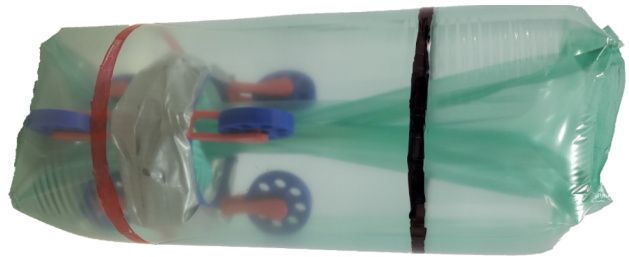


Fig. 2. Photo of the continuous skin eversion robot presented by Eken et. al [3]

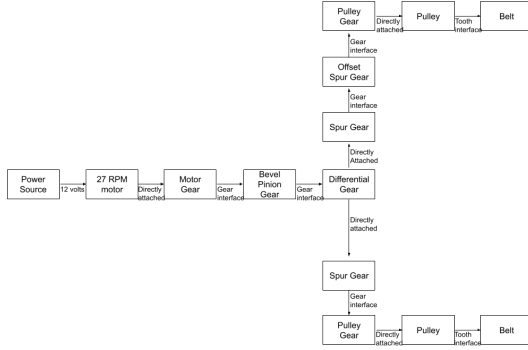


Fig. 3. Drivetrain Visualization

TABLE I
SPECIFICATION OF THE ROBOT

Pipe inner diameter	50.8 mm
Total length	63.5 mm
Total weight	86 g
Nominal voltage	DC 12 V

II. DESIGN AND FABRICATION

A. Mechanical design

To optimize the robot's speed, the gear ratio was maximized given the space constraint of fitting the robot within a 2 inch pipe. In order to determine whether the robot design was viable, the robot must successfully be able to navigate through a level 2 inch diameter pipe as well as a 90 degree elbow with a 2 inch diameter, thereby mimicking the kinds of junctions the robot would have to navigate in utility pipes. In order to decide whether such a design would be feasible, the necessary parts were found online from mechanical parts manufacturers. A motor mount was 3D printed to prevent the motor from moving. Additionally, two aluminum pieces were laser cut in order to hold all the components together.

As displayed in Figure 3, the belted pipe robot contains a primarily gear-based drivetrain. A 27 revolutions per minute motor, wired to a 12 volt power supply, has a motor gear attached to its shaft. The motor gear turns a bevel pinion gear, which then rotates in input for the differential gear. Both of

the output shafts of the differential gears each have a spur gear attached to them. One of the spur gears rotates an offset spur gear in order to eventually rotate each of the pulleys in opposite directions. Then the other spur gear and the offset spur gear each rotate a larger pulley gear, which is glued to a driving pulley. Those two pulleys rotate in opposite directions, rotating two timing belts which push and rotate against opposite sides of the pipe, thereby propelling the robot forwards.

III. FORCE AND SPEED ANALYSIS OF THE ROBOT

In the vertical direction, the robot is supported by a small wheel aligned with the direction of travel. The wheel bears the robot's gravitational force (W), as the pipe's vertical normal force (N_v) is equal in magnitude and opposite in direction to W .

$$W = m * g, W = -N_v.$$

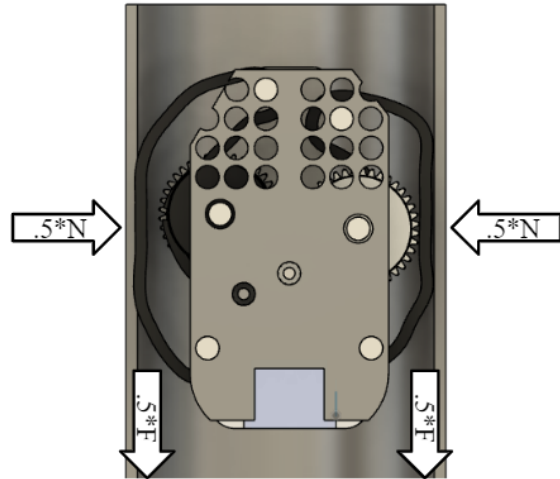


Fig. 4. Normal and Friction Forces (top view)

A. Force Analysis

In order for the pipe robot to propel itself through pipes, the belts must apply a force to the walls that overcomes the static inertia of the robot. The

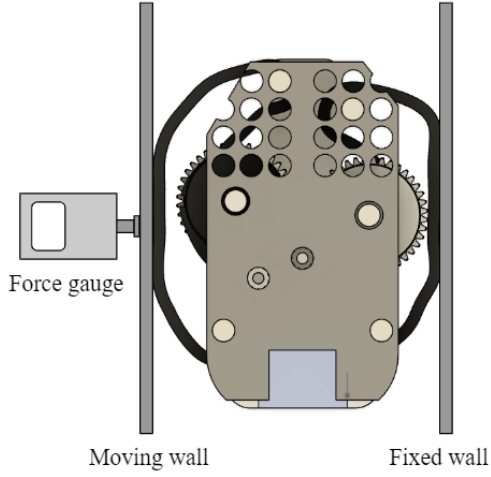


Fig. 5. Experimental setup for measuring normal force (top view)

robot functions by applying a fricative force to the pipe walls parallel and opposite in direction to its motion. So, for the robot to successfully move, the force of friction (F) applied by the belts must be equal to or greater than the minimum force required to move the robot (G) from rest. The total normal force of the pipe walls onto the belts was calculated by using a force gauge to measure the force required to push the belts of the prototype together until the total width of the robot was 2 inches, as shown in Fig. 5. This simulates the normal force applied by the sides of the pipe onto the belts. Through this process, the normal force (N) was calculated to be 1.2 N. By using a force gauge the minimum force required to move the robot from rest (G) was found to be 0.5 N.

$$F = \mu * N, F \geq G.$$

The coefficient of static friction, μ , for neoprene, the belt material, on polyvinyl chloride, the pipe material used in this experiment, is approximately 0.7. The coefficient of static friction of neoprene on other common materials used for water and gas pipes such as steel, iron, copper, and high-density polyethylene range from 0.45 to 0.90 [6]. This range of μ results in a value of F between 0.54 N

and 1.08, all of which exceed the minimum force G (0.5 N) required to overcome the static inertia of the robot.

B. Speed analysis of robot

TABLE II
THEORETICAL SPEED

	Straight pipe	90 degree elbow
Distance traveled (x)	4.0 in	10.0 in
Calculated time (t)	33 s	83 s
Theoretical speed (v)	0.12 in/s	0.12 in/s

The belted everting pipe robot was successfully able to navigate through a straight and 90 degree elbow 2 inch diameter pipe. The theoretical speed (v) of the robot was calculated using the gear ratios given in the prototype, where v_o and v_i are in output and input rotational speed, while n_o and n_i are the number of teeth on the output and input gears, respectively. The calculated time (t) was found using the equation:

$$v_o = v_i * n_o / n_i, t = x / v.$$

The experimental calculated speed (v) was found by the measured experimental straight-line length (x) and experimental time (t) by using the following equation:

$$v = x / t.$$

The motor used in the belted pipe robot was a

TABLE III
EXPERIMENTAL SPEED

	Straight pipe	90 degree elbow
Distance traveled (x)	4.0 in	10.0 in
Experimental time (t)	35 s	88 s
Calculated speed (v)	0.11 in/s	0.11 in/s

33 mm long, 27 revolutions per minute, DC motor with a 90 degree output shaft. This component was selected due to its small size and high gearbox reduction ratio (603:1), resulting in a very high stall torque (0.7392 N*m). Faster motors of the same size are available which have a lower reduction ratio, resulting in a higher motor speed of up to 136 revolutions per minute. However, given the current

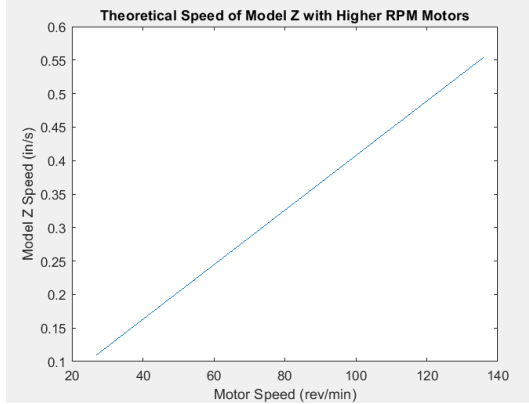


Fig. 6. Theoretical speed of the belted pipe robot with faster motors

design of the robot, those motors cannot be used due to their lower stall torque. As displayed in Figure 6, a faster motor of the same size would allow the pipe robot to achieve a speed of 0.55 in/s.

IV. EXPERIMENT

In order for the prototype to be deemed successful, the belted pipe robot was also given the qualitative criterion of having to successfully move through a 2 inch diameter pipe and navigate a 90 degree elbow. The prototype was able to move through a straight portion of polyvinyl chloride pipe in 35 seconds, as well as an elbow in 88 seconds. This serves as experimental evidence of the prototype's validity.

A video of the experiments is uploaded at <https://youtu.be/tUe7eo2wm0A?feature=shared>

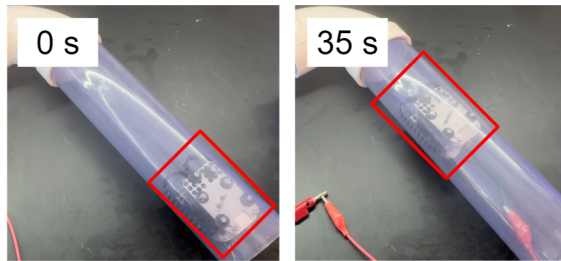


Fig. 7. The robot through a 4 inch straight pipe section

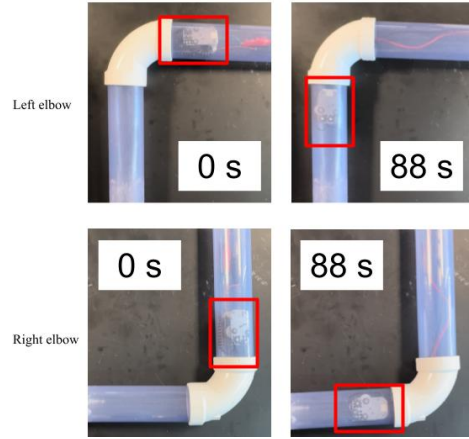


Fig. 8. The robot through a 10 inch 90 degree left and right elbow

V. CONCLUSIONS AND FUTURE WORK

The robot was able to navigate through a horizontal pipe and elbow, and its theoretical maximum speed is 0.55 in/s if the 136 RPM motor was used instead of the 27 RPM motor of the same size. Another major improvement to the current design would be to operate the robot remotely. This would require the robot to be wired to a small battery. Eventually, a localization computer chip and phone grade RGB camera could be attached to the prototype, allowing it to travel through pipe networks until damage is detected. This would help entities that use pipes frequently, such as utility companies, to pinpoint a source of damage in a pipe network and make repairs in that location. Due to its streamlined one-motor design, the successor of the belted pipe robot has the potential to be downsized such that it can navigate 1 inch pipes, if custom components are manufactured.

For future work, we will equip the endoscope on the robot for the inspection tasks. Since we designed the robot only moving in 2-inch pipes, a larger robot designed for inspection 4 to 6 inches pipeline will carry the robot within the capsule, as shown in Fig. 9, to examine 4 to 6 inches pipeline as well as 2-inch pipelines.

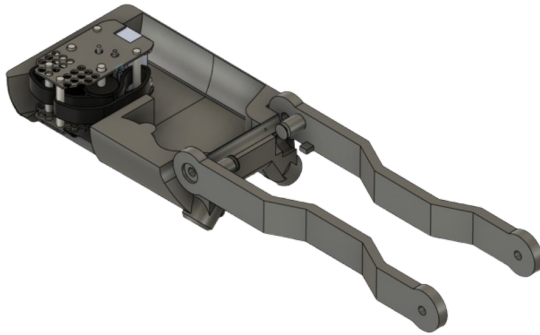


Fig. 9. The capsule for the robot

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