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In-pipe Inspection Robot for Varying Pipe Sizes

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Abstract
This paper presents a screw driven in-pipe inspection robot (IPIR) that runs on the principle of screw. The IPIR composed of a fore leg system, rear leg system, connectors and a DC motor. In this research work, a prototype of in-pipe inspection robot has been designed and developed. To verify the potency of the driving mechanism of IPIR, numbers of experiments are conducted through straight pipes, couplings, and 90-degree bends of 8 to 10 inches diameter range at 0-degree, 45 degree, and 90 degree inclination. This robot can be utilized for special tasks such as inspection, maintenance, and cleaning of water pipelines, gas pipelines, oil pipelines, and sewage systems.

Keywords: Bends, couplings, driving mechanism, inspection, screw driven

1. Introduction

A variety of pipes are being utilized to carry drinkable water, gases, and liquid waste in our modern society. Also, many types of pipes are widely used in chemical industries and in petrochemical industries for carrying petrol, diesel, oil, etc. Thusly, the pipeline has become a significant tool of transportation. But recently many complications are occurring in the pipelines due to ageing, corrosion, cracks, natural disasters, and mechanical damages from third parties and defects are occurring in the pipelines. Therefore, it becomes very difficult to find out such defects and the place of the defects, and also there is a great amount of loss. Thus, regular inspection and maintenance of pipeline must be scheduled. This inspection task can be accomplished by means of robot or it can be done by manual way. If we decide to do it manually then a large amount of time, effort, and labor are necessary to grub up the pipes that are buried in the ground. Therefore, an in-pipe robot is the most preferred option that provides various advantages such as a reduction in cost, saving in time and energy, and increases safety in the work conditions. Also, pipelines carry toxic chemicals, fluids and most of the time pipeline has a small internal diameter, 'T' joints or bends which become unreachable to human. If the robot can inspect inside the pipes, fast and accurate inspection is able to do at a low cost [1].

This paper is organized into 8 sections. Section 2 illustrates the literature review. Section 3 describes the construction and working of IPIR. Section 4 gives the design of IPIR and the selection of standard components. Section 5 presents the fabrication details and the assembly of IPIR. Section 6 provides the result and discussion. Section 7 presents the conclusion and future work.

2. Literature Review

Several researchers are working on in-pipe robotic systems which would be competent to move freely inside the pipes. Basically, in-pipe robots can be broadly classified into seven types such as wheel type,

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caterpillar type, wall-press type, walking type, inchworm type, screw type, and PIG type. This classification is made based on the difference in movement pattern and driving source [1, 2]. Most of the in-pipe inspection robots have been used one of the basic types of mechanism directly and few robots have used their combinations.

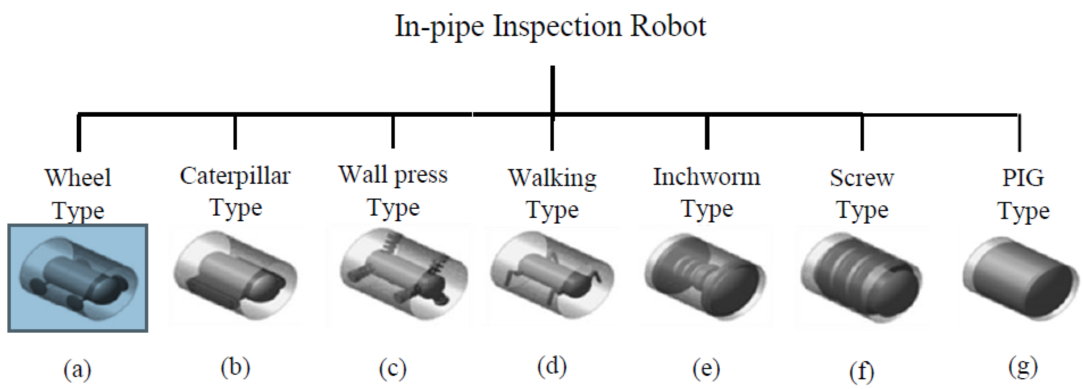

Figure 1: Classification of in-pipe inspection robots [3]

Dongwoo Lee, Jungwan Park et al. [4] have developed wall pressed wheel-type robot. That robot can move through straight pipes, elbows & 'T' joints but the weight of that robot was a little bit heavy. Yunwei Zhang and Guozheng Yan [5] have developed an in-pipe robot for long-distance inspection. Its pipe diameter adaptability is good and also, it has a provision of automatic tractive force adjustment inside the pipe. That robot can pass through slope angle and 'Z' shape joints but due to its heavy and complicated structure, it cannot pass through a vertical pipe. Muhammad Azri Abdul Wahed and Mohd Rizal Arshad [6] have presented a wall pressed wheel type pipe inspection robot which can pass through pipes of 150mm to 230mm diameter range. That robot can pass through horizontal pipes and inclined pipes of a slope not more than 30 degrees. It cannot pass through vertical pipes and other elements of the pipeline. Hun-ok Lim and Taku Ohki [7] have developed a wall pressed wheel-type pipe inspection robot. That robot can pass through horizontal pipes, vertical pipes, and 'T' joints. Fumiya Sera, Atsushi Kakogawa et al. [8] have developed a wall pressed wheel type robot for gas pipeline inspection. That robot is specially designed for bend pipes of 8 inches in diameter.

Te Li, Shugen Ma, Bin Li et al. [9] have proposed a screw-driven pipe inspection robot for different screw angles. That robot is specially designed for vertical pipes and curved pipes. In that mechanism, improvement in elastic arms was needed to move that robot in vertical pipes and other pipe elements. Taiki Nishimura, Atsushi Kakogawa, and Shugen Ma [10] have developed a new screw drive mechanism for pathway selection of in-pipe robots. That robot can travel through different horizontal T-branches and elbows. However, it could not travel through vertically oriented pipes and other pipe elements. Tao Ren, Qingyou Liu, Yujia Li et al. [11] have developed a new screw drive mechanism of varying radius. That mechanism is a bit complicated so that it is unable to pass through small pipe bends. Atsushi Kakogawa, Taiki Nishimura, and Shugen Ma [12] have presented a screw drive in-pipe robot. That robot can navigate through vertically oriented bent pipes. But still, it required finding optimal values of arm's length which can reach the pipe wall and the upper limit with minimum torque.

Ata Jahangir Moshayedi, Saeed SafaraFard et al. [13] have developed wheel type pipe inspection robot for 8 inches diameter pipes. That robot can pass through the horizontal straight pipe, bends (45 & 90 degrees), and inclined pipes of a slope are not more than 60 degrees. But it cannot pass through a vertical pipe, '+' section, and 'T' section. Junghu Min, Yuhanes Dedy Setiawan et al. [14] have presented a wheel type of robot which can move across the pipes of 300mm to 500mm diameter range.

That robot can pass through horizontal pipes and 90-degree bend pipes only. Due to its heavyweight, it cannot pass through vertical pipes. Also, it cannot pass through small diameter pipes due to its complex structure. Md RaziqAsyraf Md Zin, Khairul Salleh Mohamed Sahari et al. [15] have developed wheel type pipe inspection robot which has used magnetic wheels for vertical motion inside the pipe. The limitation of that robot is, it can pass through ferromagnetic alloy pipelines only. Ankit Nayak and S. Pradhan [16] have proposed a hybrid in-pipe inspection robot which is a combination of screw type and wall pressed wheel type robot. They have provided mathematical treatment and demonstrated the efficacy of the developed mathematical model. They have presented an initial conceptual prototype of a pipe inspection robot. However, the flexibility, steerability, and adaptability of a robot are not discussed from an experimental point of view. For brevity, other types of robots are not discussed here. For details of other types of robots, one can refer to the work of Lei Shao, Yi Wang et al. [1] and IszmirNazmi Ismail, AdzlyAnuar et al. [3].

In the present work, a screw-driven type in-pipe inspection robot is developed which is a configuration of screw type and wall pressed wheel type robot. This configuration provides good stability, more flexibility, better diameter adaptability, high tractive force, and the ability to move up in the vertical pipe.

3. Construction and Working of IPIR

3.1 Construction of IPIR

IPIR is mainly composed of a fore leg system, rear leg system, connectors, and a DC motor. The fore leg system consists of two sub leg systems. One is driving leg system and another is supporting leg system. The rear leg system is consisting of two supporting leg systems which is shown in figure 2.

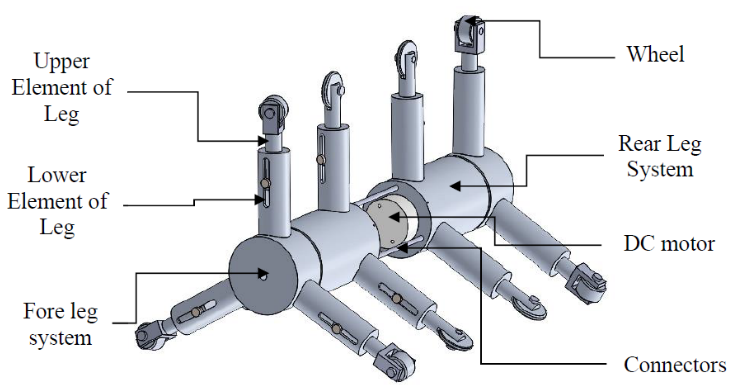

Figure 2: Solid model of In-pipe Inspection Robot

The driving leg system of the fore leg system is mounted on the DC motor shaft whereas the supporting leg systems are mounted on a motor casing. Both the driving and supporting leg systems consist of three legs that are framed at an angle of 120 degrees with reference to each other to pass through pipes of 8 inches to 10 inches diameter range. Each leg is comprised of a lower element, upper element, spring, and a wheel.

3.2 Working of IPIR

A geared DC motor with an encoder is a prime mover of IPIR. The driving leg system of fore leg system is mountain on the output shaft of a DC motor. To get a forward and backward motion of the robot in helical direction, the wheels of driving leg system are connected to the upper elements at an angle of 15 degrees, whereas wheels of supporting leg systems are kept straight. When motor is activated, the rotary motion of motor shaft is converted into helical motion at the inclined wheels. The springs are placed into the lower elements of all legs that does help to travel easily through the different pipe elements of 8 inches to 10 inches diameter range at 0 degree, 45 degree and 90 degree inclination.

3.3 Technical Specification of IPIR

The following table shows the technical specifications of IPIR.

Table 1: Technical Specifications of IPIR

Sr. No.	Parameter	Dimension
1.	Maximum Diameter Adaptability	0.25m
2.	Minimum Diameter Adaptability	0.2m
3.	Overall Length	0.3m
4.	Total Weight	2.5kg
5.	Degree of Freedom	3
6.	Drive Type	Electrical
7.	Speed	0.034m/s

4. Design of IPIR and Selection of Standard Components

In wall-press type robot spring plays a very important role. So, springs of the driving leg system and supporting leg system are designed carefully.

Table 2: Design of IPIR Components

Sr. No.	Parameter to Design/select	Parameters Considered for Design/selection	Designed/selected Parameters
1.	Linear velocity of a robot	Helix angle, $\alpha = 15°$ Minimum diameter, D = 0.2 m	$V_H = 0.126$ m/s, $V_L = 0.034$ m/s
2.	Speed of motor	Helical velocity, $V_H = 0.126$ m/s Radius of the wheel, r = 0.1 m	Motor speed, N = 12 rpm
3.	Driving leg spring force & Spring stiffness	Mass of robot = 2.5 kg Coefficient of friction, $\mu_s = 0.15$ Minimum compression of spring, $\delta_{min} = 0.015$ m	Spring Stiffness, $k_1 = 3389.9467$ N/m Spring force, $[F_{s_1}]_{max} = 135.5979$ N
4.	Driving leg spring wire diameter	Stiffness of Spring, $k_1 = 3389.9467$ N/m Outer diameter, $D_o = 0.016$ m Free length, $L_f = 0.065$ m	Spring wire diameter, d = 0.00221 m

5.	Supporting leg spring force & Spring stiffness	Mass of robot = 2.5 kg Coefficient of friction, μ_s = 0.15 Minimum compression of spring, δ_{min} = 0.015 m	Spring Stiffness, k_2 = 908.3333 N/m, Spring force, $[F_{S_2}]_{max}$ = 36.3333 N
6.	Supporting leg spring wire diameter	Stiffness of Spring, k_2 = 908.3333 N/m Outer diameter, D_o = 0.016 m Free length, L_f = 0.065 m	Spring wire diameter, d = 0.00114 m
7.	DC motor	Power required, P = 5 watts, Motor speed, N = 12 rpm	Planetary DC motor, V = 12 v, I = 0.9 Ah, N = 24 rpm & P = 7 watt
8.	Battery	Power required, P = 5 watts	Lithium-ion battery, V = 11.1 v & A = 4 Ah

5. Fabrication of IPIR

5.1 Fabrication details of IPIR Components

Aluminum 6063 is lightweight and has good strength hence Aluminum is employed for the fabrication of the robot body and other elements. All parts of the robot are fabricated on a lathe machine, drilling machine, and milling machine.

Table 3: Fabrication Details of IPIR Components

Sr. No.	Part Name	Material Used	Machines Used	Machine Operations	Qty.
1.	Driving leg spring	Stainless steel	Spring machine	Spring machine operation	3
2.	Supporting leg spring	Stainless steel	Spring machine	Spring machine operation	9
3.	Connectors	Mild Steel	-	Cutting & facing	3
4.	Rotor	Al 6063	Lathe, Drilling & Hand tap	Turning, facing, drilling & tapping	2
5.	Lower element of leg	Al 6063	Lathe & Milling	Turning, facing, boring, treading & slot	12
6.	Upper element of leg	Al 6063	Lathe, Drilling, Milling & Hand tap	Turning, facing, drilling, sleeting & tapping	12
7.	Wheel	Mild steel	Lathe & Drilling	Turning, facing, drilling, knurling	12

5.2 Assembly of IPIR

The following figure shows the fabricated model of an in-pipe inspection robot.

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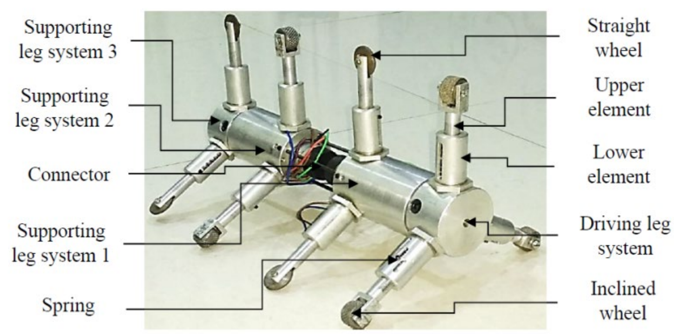

Figure 3: Prototype of In-pipe Inspection Robot

6. Result and discussion

6.1 Result

To confirm the potency of the driving mechanism and diameter adaptability of IPIR, its trials are conducted through straight pipes, couplings, and 90 degree bends of 8 inches, 9 inches and 10 inches diameter pipe at 0 degree, 45 degree, and 90 degree inclination.

(a) 9 inches straight pipe at 0° (b) 8 inches straight pipe at 45° (c) 8 inches coupling at 0°

(d) 9 inches coupling at 45° (e) 10 inches 90° bend at 0° (f) 8 inches 90° bend at 90°

Figure 4: Movement through 8 inches, 9 inches and 10 inches diameter pipe elements at 0 degree, 45 degree and 90 degree inclination

Following table shows the linear velocity of robot through straight pipe, coupling, and 90 degree bend of 8 inches, 9 inches and 10 inches diameter pipe. All experiments are conducted through PVC pipe elements of 0.75m length.

Table 4: Experimental Results in 8, 9 and 10 inches Diameter Pipe Elements

Pipe Element and its position	Linear velocity (m/s)					
	Through 8 inches diameter pipe		Through 9 inches diameter pipe		Through 10 inches diameter pipe	
	Forward direction	Backward direction	Forward direction	Backward direction	Forward direction	Backward direction
Straight pipe at 0° inclination	0.0144	0.0139	0.0242	0.0203	0.0357	0.0326
Straight pipe at 45° inclination	0.0192	0.0106	0.0227	0.0121	0.0326	0.0167
Straight pipe at 90° inclination	0.0300	0.0070	0.0375	0.0103	0.0417	0.0144
Coupling at 0° inclination	0.0134	0.0125	0.0208	0.0192	0.0313	0.0341
Coupling at 45° inclination	0.0167	0.0104	0.0192	0.0123	0.0341	0.0188
Coupling at 90° inclination	0.0313	0.0068	0.0357	0.0094	0.0375	0.0136
90-degree Bend at 0° inclination	0.0155	0.0152	0.0165	0.0164	0.0169	0.0170
90-degree Bend at 45° inclination	0.0157	0.0155	0.0162	0.0161	0.0164	0.0164
90-degree Bend at 90° inclination	0.0162	0.0161	0.0161	0.0163	0.0162	0.0161

6.2 Discussion

During the experimentation, it has been observed that the maximum linear velocity of the robot is found 0.0417m/s in the downward direction for 10 inches diameter straight pipe at 90 degree inclination whereas the minimum linear velocity of the robot is found 0.0068m/s in the upward direction for 8 inches diameter coupling at 90 degree inclination. Also, the linear velocity of robot is found less in backward direction compared to forward direction.

7. Conclusions

A screw-driven wall pressed wheel type in-pipe inspection robot has been designed which is capable to navigate through the pipe elements of 8 inches to 10 inches diameter range. Moreover, the prototype of IPIR is fabricated to confirm the potency of the steeringmechanism in straight pipes, couplings, and 90 degree bends of 8 inches, 9 inches, and 10 inches diameter at 0 degree, 45 degree, and 90 degree inclination. Based on the literature reviewed and experimental study of IPIR it is found that the steerability, mobility, and adaptability of IPIR is better than existing pipe inspection robots. The novelty of this robot is its adaptability for larger diameter pipe elements with higher variability. So, experimentally it has been concluded that the overall performance of this robot is better than existing in pipe inspection robots.

In the future, ultrasonic sensors will be mounted on a robot body to discover the defects and points of defects inside the pipe. Also, a micro camera will be installed on the fore leg system for better controllability and real-time in-pipe visibility. This developed IPIR shall be redesigned in the future to pass through 'T' joints.

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