Design and Development of In-pipe Inspection Robot for Various Pipe Sizes

Atul Gargade1* and Shantipal Ohol1

1Mechanical Engineering Department, College of Engineering Pune, India.

E-mail: gargadeaa14.mech@coep.ac.in

Abstract. In-pipe inspection robots are designed to pull out the human role from work load and risky working circumstances. In this paper an in-pipe inspection robot version 2 (IPIR version 2) is presented which composed of two driving leg systems, two supporting leg systems and a connecting body. Novelty of version 2 is its stability and diameter adaptability. Stability of version 2 is enhanced by adding two supporting leg systems in version 1 and diameter adaptability of version 2 is improved by optimizing its spring design. All major components of version 2 are designed safely. Solid modelling of all robot parts and its assembly is carried out in Solidworks 16. Mathematical modelling of version 2 is carried by Lagrange’s method. A planetary geared DC motor with encoder (IG42E-104K) is used as prime mover of IPIR version 2. This robot has mainly employed aluminium as structural material. To verify the efficacy of driving mechanism, several experiments of version 2 are conducted in horizontal pipes, vertical pipes and couplings of 8 inches to 10 inches diameter range. This IPIR version 2 will be employed for offline visual checking of various pipe components like horizontal pipes, vertical pipes and couplings in water pipelines, gas pipelines and drain pipes etc.

Keywords: In-pipe inspection robot version 2 (IPIR version 2); driving mechanism; planetary geared DC motor; defects.

1. Introduction
From last couple of decades, robotics is becoming one of the most quickly expanding fields. As we know, variety of pipes is being used to build valuable lifelines like gas supply, water supply and sewerage systems in our modern community. Therefore, pipeline has become a crucial component of conveyance. In fact, pipeline has become an integrated module of dissimilar types of sectors, such as power plants, crude oil companies and suburban water supply, agriculture field and so on. But due to the years of usage of pipelines, defects like cracks, aging and corrosion takes place. Even blockages are also seen in the pipeline. Sometimes defects are taking place due to natural disasters and mechanical damages from unbiased observer. Therefore, it becomes very difficult to search such defects and their locations. Thus, maintenance plan of such pipelines should be scheduled. If we accomplish inspection activity by manual way then great amount of efforts, labours and time is required to dig out the pipes that are covered under the floor. The utmost reason of inventing in pipe inspection robot is to withdraw human being and come out with a fast and accurate inspection at low cost [1, 2].
Therefore, in-pipe robots are broadly classified into actively moving robots and passively moving robots. This classification is made on the basis of difference in operating source and controllability of steering mechanism. Active locomotion robots can be further sorted into six categories which are shown in figure 1. Pig type is a classic example of passively moving robots [3].

![Diagram of In-pipe Inspection Robot]

**Figure 1.** Sorting of in-pipe robots (a) Wheel type (b) Wall press type (c) Screw type (d) Walking type (e) Inchworm type (f) Caterpillar type (g) Pig type [4]

A wheel type robot shown in figure 1(a) is most preferred type of pipe inspection robot. Advantage of this type of robot is its very simple design. The wall press type robot shown in the figure 1(b) gives most tractive force as compared to other types. Due to high tractive force it can climb in vertical pipelines by pressing the wall by whatever mode they employ. In this type, design of robot is decided by the particular application. Figure 1(c) displays screw type (helical drive type) robot which follow the principle of screw. When it travel in the pipeline, it follows the helical path. Figure 1(d) depicts a walking type which is generally called as crawler robot. Advantage of this type of robot is that it can walk on any type of surface. Figure 1(e) shows inchworm type robot, which emulate motion of inchworm. Its movement through pipe is very slow like inchworm but it can be used for very small diameter pipelines. Figure 1(f) illustrates the robot with caterpillars. This type of robot comes up with additional grips than wheel type robot, which helps to reduce the slips inside the pipe. Figure 1(g) displays a pig type of in-pipe inspection robot. In this type fluid pressure is used to drive the robot passively inside the pipeline. Generally this type of robot is preferred for inspection of large diameter pipelines [5, 6].

This paper is arranged in VIII sections. Section II presents literature review of in-pipe inspection robot. Section III describes the construction and working of IPIR version 2. Section IV gives mechanical design and selection of version 2 components. Section V provides mathematical modelling of IPIR version 2. Section VI gives fabrication details and assembly of version 2. Section VII provides the result and discussion. Section VIII presents conclusion and future work.

### 2. Literature Review

Since long back, several researchers are working on robotic systems which can travel effectively and easily through the pipelines. Some of the most important and related pipe inspection robots are described in literature. Atsushi Kakogawa et al. [7] have presented screw drive in-pipe robot. This robot can travel across the vertically positioned bent pipes but still it required finding optimal values of arm length to reach to the pipe wall and the upper limit with minimum torque. Atul Gargade et al.
[8] have proposed a wall pressed wheel type in-pipe inspection robot. This robot can pass through horizontal and vertical pipes of 140mm to 200mm diameter range. It does not pass through bends and couplings. Muhammad Azri Abdul Wahed and Mohd Rizal Arshad [9] have presented 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 degree. It cannot pass through vertical pipes and other elements of pipeline. Hun-ok Lim and Taku Ohki [10] have developed wall pressed wheel type pipe inspection robot. That robot can pass through horizontal pipes, vertical pipes and ‘T’ joints. R. K. Jain et al. [11] have proposed a virtual prototype of in-pipe inspection robot. That robot has employed scissor mechanism for inspection of large diameter pipeline of 500mm to 1000mm diameter range. Ankit Nayak and S. Pradhan [12] have proposed an in-pipe inspection robot which is combination of screw type and wall pressed wheel type robot. They have provided mathematical treatment and demonstrated the efficacy of developed mathematical model. They have presented initial conceptual prototype of pipe inspection robot.

Majority of in-pipe inspection robots have used one of the basic types of mechanism directly whereas some robots have used combination of basic types. This paper presents a screw driven wall pressed wheel type in-pipe inspection robot version 2. This version is configuration of screw type and wall pressed wheel type robot. This presented configuration is providing better stability and diameter adaptability than existing screw driven wall pressed wheel type in-pipe inspection robot.

3. Construction and Working of IPIR version 2

3.1. Construction and Working of IPIR version 1

IPIR version 1 was consisting of forward leg system, backward leg system and a body. That version was able to pass through horizontal and inclined pipes of 10 inches diameter only. Therefore, its diameter adaptability inside different pipe sizes was poor. Weight of version 1 was 2.2 kg. Due to high weight its steerability in vertically pipe was very poor.

![Working model of IPIR version 1](image)

Figure 2. Working model of IPIR version 1 [13]

Therefore, IPIR version 2 has been developed to overcome the drawbacks of IPIR version 1. Stability of IPIR is improved in version 2 by adding two supporting leg systems. Spring design of version 1 is optimized to pass through pipes of 8 inches to 10 inches diameter range.

3.2. Construction and Working of IPIR version 2

In-pipe inspection robot version 2 mainly composed of a forward leg system, backward leg system, and a connecting body. Both the leg systems are mirror images of each other in construction. Each leg system consists of two sub leg systems. One is driving leg system with inclined wheels and another is
supporting leg system with straight wheels. Driving leg systems of fore leg systems is mounted on the DC motor shaft whereas supporting leg system is fixed on a robot body. Both driving and supporting leg systems consists of three legs which are framed at an angle of 120 degree to one another to travel through pipes of 8 inches to 10 inches diameter range. Each leg comprised of a lower element, upper element, spring and a wheel which is shown in figure 3. To get better stability in vertical pipe wheels of both the leg systems are knurled.

Figure 3. Solid model of IPIR version 2

To get forward and backward motion of robot in spiral direction, wheels of driving leg systems are connected to top element at an angle of 15 degree. Wheels of supporting leg systems are kept at 90 degree to get rolling motion in to and fro direction. Springs are placed into lower element of each leg which does help to advance easily inside pipes of 8 inches to 10 inches diameter range. A planetary geared DC motor with encoder (IG42E-104K) is prime mover of IPIR version 2. In this robot, aluminium is used as structural material for fabrication of major parts.

3.3. Specification of IPIR version 2
Following table shows the specifications of IPIR version 2.

Table 1. Specifications of IPIR version 2

| Sr. No. | Parameter       | Dimension |
|---------|-----------------|-----------|
| 1.      | Length          | 300 mm    |
| 2.      | Diameter (max)  | 250 mm    |
| 3.      | Diameter (min)  | 200 mm    |
| 4.      | Weight          | 2 kg      |
| 5.      | Linear Velocity | 113.5 mm/s|

4. Mechanical Design and Selection of IPIR version 2 Components
Design of all major components and selection of some specific components of IPIR version 2 is shown in following table.
Table 2. Design of IPIR version 2 Components

| Sr. No. | Parameter to Design | Parameters Considered for Design | Designed Parameters |
|---------|---------------------|----------------------------------|---------------------|
| 1.      | Linear velocity of robot | Helix angle, $\alpha = 15^\circ$ Diameter, $D = 270$ mm | $V_H = 424$ mm/sec, $V_L = 113.5$ mm/sec |
| 2.      | Speed of motor | Helical Velocity, $V_H = 424$ mm/sec Radius of wheel, $r = 135$ mm | Motor speed, $N = 30$ rpm |
|         | Spring force & Spring stiffness | Mass of robot considered for design, $m = 4$ kg Coefficient of friction, $\mu_s = 0.3$ Minimum compression of spring, $\delta_{\text{min}} = 15$ mm | Spring force, $[F_{S_{\text{min}}} = 40.6793$ N Spring Stiffness, $k = 2.7119$ N/mm |
| 3.      | Spring wire diameter | Stiffness of Spring, $k = 2.711$ N/mm Outer diameter, $D_o = 16$ mm Free length, $L_f = 60$ mm | Spring wire diameter, $d = 2.1$ mm |
| 4.      | Power required | Weight of robot = 40 N Frictional force = 132 N Linear velocity = 113.5 mm/sec | Power required, $P_{\text{required}} = 20$ watt |
| 5.      | Selection of battery | Select Lithium-iron 12v & 2.5 Ah | Power provided, $P_{\text{provided}} = 30$ watt |
| 6.      | Design of motor shaft | Shear stress, $\tau_{\text{max}} = 90$ N/mm$^2$ Power, $P = 20$ watt | Motor shaft diameter, $d = 7$ mm |

5. Mathematical Modeling of IPIR version 2

Dynamic Analysis of IPIR version 2 by Lagrange’s Energy Method:

Here robot is performing general plane motion along $x$-direction.

\[ \mathbf{R} = r \mathbf{\theta} + \mathbf{x} \]

\[ \mathbf{V} = r \mathbf{\dot{\theta}} + \mathbf{\dot{x}} \]

\[ \mathbf{a} = r \mathbf{\ddot{\theta}} + \mathbf{\ddot{x}} \]

\[ \mathbf{F}_{\text{max}} = 90 \text{ N/mm}^2 \]

\[ P = 20 \text{ watt} \]

\[ d = 7 \text{ mm} \]
Equation of driving force is,
\[ F(t) = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{x}} \right) - \frac{\partial L}{\partial x} \]  
(1)

Equation of driving torque is,
\[ T(t) = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}} \right) - \frac{\partial L}{\partial \theta} \]  
(2)

As we know energy equation is,
\[ T.E. = K.E. - P.E. \quad \therefore \quad L = \left[ \frac{1}{2} m v^2 + \frac{1}{2} I \dot{\theta}^2 \right] - \left( \frac{1}{2} kx^2 + \frac{1}{2} k_t \theta^2 \right) \]  
(3)

By differentiating equation (3)
We get,
\[ \frac{\partial L}{\partial x} = -kx \]
\[ \frac{\partial L}{\partial \dot{x}} = m (\ddot{x} + r \ddot{\theta}) \sin \alpha + I \left( \frac{\dot{x} + r \dot{\theta}}{r^2} \right) \cos^2 \alpha \]
\[ \frac{\partial L}{\partial \theta} = -k_t \theta \]
\[ \frac{\partial L}{\partial \dot{\theta}} = mr (\ddot{x} + r \ddot{\theta}) \sin^2 \alpha + I \left( \frac{\dot{x} + r \dot{\theta}}{r^2} \right) \cos \alpha \]
\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{x}} \right) = m (\dddot{x} + r \dddot{\theta}) \sin \alpha + I \left( \frac{\ddot{x} + r \ddot{\theta}}{r^2} \right) \cos \alpha \]
\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}} \right) = mr (\dddot{x} + r \dddot{\theta}) \sin^2 \alpha + I \left( \frac{\ddot{x} + r \ddot{\theta}}{r^2} \right) \cos \alpha \]

\[ \therefore \text{Equation (1) will become,} \]
\[ F(t) = m(\dddot{x} + r \dddot{\theta}) \sin^2 \alpha + \frac{I \cos^2 \alpha}{r^2} (\dddot{x} + r \dddot{\theta}) + kx \]  
(4)

\[ \therefore \text{Equation (2) will become,} \]
\[ T(t) = mr (\dddot{x} + r \dddot{\theta}) \sin^2 \alpha + \frac{I \cos^2 \alpha}{r} (\dddot{x} + r \dddot{\theta}) + k_t \theta \]  
(5)

Where,
\[ m = \text{mass of robot (kg)} \]
\[ r = \text{length of robot leg (mm)} \]
\[ \alpha = \text{helix angle of wheel (degree)} \]
\[ k = \text{equivalent stiffness (N/mm)} \]
\[ k_t = \text{torsion stiffness of wheel assembly (N.mm/rad)} \]
\[ I = \text{inertia of robot (kg.mm}^2) \]
\[ \theta = \text{angular displacement of robot (rad)} \]
\( \dot{\theta} \) = angular velocity of robot (rad/s)
\( \ddot{\theta} \) = angular acceleration of robot (rad/s\(^2\))
\( x \) = linear displacement of robot (mm)
\( \dot{x} \) = linear velocity of robot (mm/s)
\( \ddot{x} \) = linear acceleration of robot (mm/s\(^2\))

\( F(t) \) = driving force of robot (N)
\( T(t) \) = driving torque of robot (N.mm)

6. Fabrication and Assembly of IPIR version 2 Components

6.1. Fabrication Details of IPIR version 2 Components

All components of robot are fabricated by using lathe machine, milling machine and drilling machine. Hand tap is used for tapping operation. Due to lightweight and good strength of aluminum, it is used for fabrication of robot body and other parts of version 2.

| Sr. No. | Component Name | Material Used | Machine Operations | Machines Used | Fabricated Component Qty |
|---------|----------------|---------------|--------------------|---------------|--------------------------|
| 1.      | Rotor          | Aluminium     | Turning, facing,   | Lathe,        | 4                        |
|         |                |               | drilling &        | Drilling &    |                          |
|         |                |               | Tapping           | Hand tap      |                          |
| 2.      | Bottom element | Aluminium     | Turning, threading, | Lathe &      | 12                       |
|         |                |               | boring, facing &   | Milling       |                          |
|         |                |               | Slot              |               |                          |
| 3.      | Top element    | Aluminium     | Turning, drilling, | Lathe,        | 12                       |
|         |                |               | sleeting, facing & | Milling,      |                          |
|         |                |               | tapping           | Drilling &    |                          |
|         |                |               |                   | Hand tap      |                          |
| 4.      | Wheel          | Mild steel    | Turning, drilling, | Lathe &      | 12                       |
|         |                |               | facing &          | Drilling      |                          |
|         |                |               | Knurling          |               |                          |
| 5.      | Check nut      | Aluminium     | Turning, boring    | Lathe &      | 12                       |
|         |                |               | & threading       | Milling       |                          |
| 6.      | Spring         | Stainless steel| Spring machine    | Spring        | 12                       |
|         |                |               | operation         | machine       |                          |
6.2. Working Prototype of IPIR version 2
Following figure shows fabricated model of IPIR version 2.

![Working model of IPIR version 2]

**Figure 4.** Working model of IPIR version 2

7. Result and Discussion

7.1. Result

To verify the efficacy of driving mechanism of version 2, its movement is conducted through horizontal pipes, vertical pipes and couplings of 8 inches and 10 inches diameter. All experiments are conducted for pipe elements of 900mm length.

![Horizontal Pipe](image1)
![Vertical Pipe](image2)
![Coupling](image3)

**Figure 5.** Movement of IPIR version 2
7.1.1. Movement through 8 inches Diameter Pipe

Table 4. Experimental results in 8 inches diameter pipe

| Pipe Position       | Linear Displacement (mm) | Time (sec) | Linear Velocity (mm/s) |
|---------------------|--------------------------|------------|------------------------|
| Horizontal forward  | 900                      | 120.6      | 7.4626                 |
| Horizontal backward | 900                      | 73.2       | 12.2950                |
| Vertical downward   | 900                      | 60.3       | 14.9253                |
| Vertical upward     | 900                      | 183.9      | 4.8940                 |
| Coupling forward    | 900                      | 122.8      | 7.3290                 |
| Coupling backward   | 900                      | 75.1       | 11.9840                |

7.1.2. Movement through 10 inches Diameter Pipe

Table 5. Experimental results in 10 inches diameter pipe

| Pipe Position       | Linear Displacement (mm) | Time (sec) | Linear Velocity (mm/s) |
|---------------------|--------------------------|------------|------------------------|
| Horizontal forward  | 900                      | 36.9       | 24.3902                |
| Horizontal backward | 900                      | 27.3       | 32.9670                |
| Vertical downward   | 900                      | 18.9       | 47.6190                |
| Vertical upward     | 900                      | 56.7       | 15.8730                |
| Coupling forward    | 900                      | 38.6       | 23.3161                |
| Coupling backward   | 900                      | 28.6       | 31.4685                |

It has been observed that least linear velocity of version 2 is found in vertically upward direction for 8 inches diameter pipe whereas higher linear velocity is found in vertically downward direction for 10 inches diameter pipe. Also velocity of robot is greater in reverse direction compared to forward direction.
7.2. Discussion
After real time experimentation of both the versions, their comparative study has been made which is given in following table.

| Performance Indicator | IPIR version 1 | IPIR version 2 |
|-----------------------|---------------|---------------|
| Weight                | 2.2 kg        | 2 kg          |
| No. of actuators      | 01            | 01            |
| Steerability          | Poor          | Good          |
| Mobility              | Horizontal pipes, Inclined pipes | Horizontal pipes, Vertical pipes & couplings |
| Size and shape adaptability | 10 inches pipe | 8 to 10 inches pipes |

8. Conclusion and Future Work
IPIR version 2 have been developed which can travel easily through horizontal pipes, vertical pipes and couplings of 8 inches and 10 inches diameter. All major components of version 2 are designed carefully. Solid model of IPIR is created in Solidworks 16. Weight of IPIR is reduced in version 2. The efficacy of driving mechanism of version 2 has been verified by conducting its movement through horizontal pipes, vertical pipes and couplings of 8 inches and 10 inches diameter. On the basis of literature reviewed and experimental study of version 2, it has been concluded that IPIR version 2 is better in steerability and diameter adaptability than existing screw driven wall presses wheel type pipe inspection robots.

In future, design of robot will be optimized to pass through 45 degree and 90 degree bends. An ultrasonic sensor will be mounted on a robot body to detect the obstruction and point of obstruction inside the pipe. A CCD camera will be installed on forward leg system for real time in-pipe visibility.

References
[1] Atul Gargade and Shantipal Ohol. 2016. Design and Development of In-Pipe Inspection Robot. American International Journal of Research in Science, Technology, Engineering & Mathematics. USA. pp. 104-109.
[2] Atul Gargade and Shantipal Ohol. 2016. Development of In-pipe Inspection Robot. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE). USA. pp. 64-72.
[3] Lei Shao, Yi Wang et al. 2015. A Review over State of the Art of In-Pipe Robot. Proceeding of 2015 IEEE International Conference on Mechatronics and Automation. China. pp. 2180-2185.
[4] Atul Gargade and Shantipal Ohol. 2020. A Review Over In-pipe Inspection Robot. Journal of SEYBOLD Report. pp. 1459-1468.
[5] Amit Shukla and Hamad Karki. 2016. Application of robotics in onshore oil and gas industry – A review part – I. Robotics and Autonomous systems. pp. 490-506.
[6] Izsmir Nazmi Ismail, Adzly Anuar et al. 2012. Development of In-pipe Inspection Robot: a Review. IEEE Conference on Sustainable Utilization and Development in Engineering and Technology. Malaysia. pp. 310-315.
[7] Atsushi Kakogawa, Taiki Nishimura and Shugen Ma. 2016. Designing arm length of a screw drive in-pipe robot for climbing vertically positioned bent pipes. Robotica. pp. 306-327.

[8] Atul Gargade, Dhanraj Tambuskar and Gajanan Thokal. 2013. Modelling and Analysis of Pipe Inspection Robot. International Journal of Emerging Technology and Advanced Engineering. pp. 120-126.

[9] Muhammad Azri Abdul Wahed and Mohd Rizal Arshad. 2017. Wall-press Type Pipe Inspection Robot. IEEE 2nd International Conference on Automatic Control and Intelligent Systems (I2CACIS 2017). Malaysia. pp. 185-190.

[10] Hun-ok Lim and Taku Ohki. 2009. Development of Pipe Inspection Robot. ICROS-SICE International Joint Conference. Japan. pp. 5717-5721.

[11] R. Jain, Abhijit Das and A. Mukherjee. 2019. Design Analysis of Novel Scissor Mechanism for Pipeline Inspection Robot (PIR). Proceedings of the 4th International Conference of Robotics Society of India at Indian Institute of Technology Madras. India. pp. 1-6.

[12] Ankit Nayak and S. Pradhan. 2014. Design of a New In-pipe Inspection Robot. 12th Global Congress on Manufacturing and Management (GCMM). pp. 2081-2091.

[13] Atul Gargade and Shantipal Ohol. 2017. Development of Actively Steerable In-pipe Inspection Robot for Various Sizes. Proceedings of the 3rd International Conference of Robotics Society of India at Indian Institute of Technology Delhi. India. pp. 1-5.