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## Design of a New In-Pipe Inspection Robot

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### Abstract

Basically robots are designed in such way that they remove human intervention from labour intensive and hazardous work environment, sometimes they are also used to explore inaccessible work places which are generally impossible to access by humans. The inspection of pipe comes in same category because they carry toxic chemicals, fluids and most of the time has small internal diameter or bends which become inaccessible to human. The complex internal geometry and hazard content constraints of pipes demand robots for inspection of such pipes in order to check corrosion level of pipe, recovery of usable parts from pipe interior, sampling of sludge and scale formation on pipe internal surface etc. Several designs of In-pipe inspection robots (IPIR) have been proposed in the literature to solve the problems related with inspection of these complicated internal geometries. Designing of an in-pipe inspection robot (IPIR) is a difficult task and hence the designer must take care of the design issues like Mobility, Steer ability, Turning radius, Size and shape adaptability, Online adaptability, Flexibility, Stability, Autonomous operation and obstacle avoidance, Efficiency at uneven surface, Safe operation, Material selection, Type of task to be performed inside the pipe, Number of actuators, Operation in active pipe line, Retrieval of robot, User friendly navigation and control system, Range of operation, Quantitative analysis of defects inside the pipe. Based on above, this research work presents investigations into design issues pertaining to development of In-pipe inspection robotics and proposes a new model of an In-pipe inspection robot to overcome some critical design issues. This proposed model is a screw drive type wall press adaptable wheeled In-pipe inspection robot. It is able to move through vertical, horizontal pipes and it can easily pass through elbow of a pipe line. This model comprises of three modules- rotor, stator and control unit. The Rotor module has three wheels mounted on the outer periphery with a helix angle of 15°. Wheels of rotor follow the helical path on the internal surface of pipe line and move in the longitudinal direction inside the pipe.

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**Keywords:** In pipe inspection robot, Design issues, IPIR, Screw drive, Shape adaptability, Modular design

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A geared DC motor of 200RPM is connected to rotor by a flexible sleeve coupling. Due to its flexibility motor can transmit torque to rotor even in case of minor misalignments and can easily be stopped at any point of journey inside the vertical or horizontal pipeline, thereby eliminating the need of braking system to achieve stability. Stator module is the housing of motor and it contains three spring loaded wheels on the outer periphery. Control Module of robot consist battery and wireless control unit. Spring loaded wheels of rotor and stator provide it shape adaptability and enhance friction between wheels and pipe interior.

## 1. Introduction

Robotics is one of the fastest growing engineering fields, presently they are used for wide variety of works specially in manufacturing industries e.g. spot welding, loading and unloading of tool and work piece, painting etc. Primarily robots are designed in such way that they reduce human intervention from labour intensive and hazardous work environment; sometimes it is also used to discover inaccessible work place which is generally impossible to access by humans. The complex internal geometry and hazard content constraints of pipes require robots for inspection purpose. With these constraints, inspection of pipe becomes so more necessary that, tolerating it may lead to some serious industrial accidents which contaminate environment and loss of human lives also. For inspection of such pipes, robot requirement is must especially in order to check corrosion level of pipe, recovery of usable parts from pipe interior, for sampling of sludge and scale formation on pipe internal surface etc.

Designing of a new in-pipe inspection robot is carried out in this research work. It involves kinematic and dynamic analysis of screw drive type robot. Kinematic calculations are performed to find the trajectory of rotor motion and to also to analyze the motion of robot in straight and curved pipeline. From the dynamic equation of robot the effect of frictional force, drag force and mass of the robot are analyze on the robot to find the required minimum motor torque for moving in horizontal, inclined and vertical pipelines. After performing design steps, solid model is prepared in UGNX of the proposed robot. Motion simulation and experimental study are performed with the help of this solid model and an initial robot prototype.

### 1.1. Existing Research

In-Pipe Inspection Robots (IPIRs) are widely used in petrochemical, water supply and fluid transportation industries. Many researchers have been done work to develop new in-pipe robots to enhance various aspects of in pipe inspection robot like vision, control and motion or robot. Research work of these researchers are reviewed to find the design philosophy, capabilities and limitation of different types of robot on the bases of review it has been found that the in-pipe robot can be classified in to three main categories and eight sub categories as depicted through Fig.1.

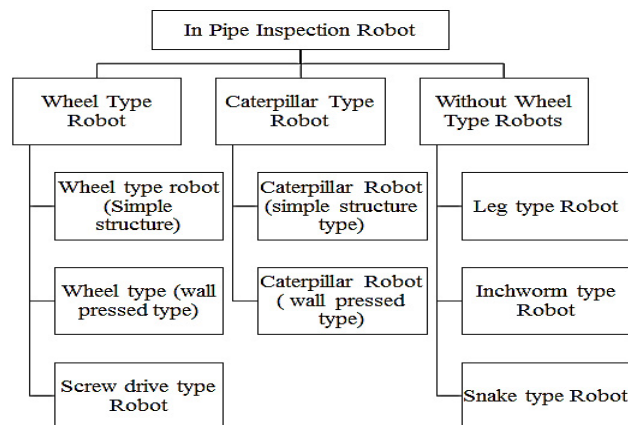


Fig.1. Classification of IPIR

In wheel type robots [1,2], wheels are directly connected to motor to get desired locomotion. They have simple structure, and better velocity control with small car like structure while in wall pressed robot [3,4], the wheels are mounted on the elastic arms which provide adaptability and required frictional force to the robot. Screw type robots [5,6] have two modules a stator and a rotor. Rotor composed of three tilted wheels at a specific angle. Rotor is directly connected to motor and it converts the rotation of motor in to translation of robot. Stator of screw drive type robot consist three straight wheels which provide the stability to the robot and prevent the robot from reaction force, comes due to rotation of rotor. Caterpillar type robot has two categories viz. caterpillar type robot simple structure[7,8] and caterpillar robot wall pressed type [9,10] structure. Caterpillar robot simple structure has belt bound wheels which are connected to actuators. Belt bounded wheels provide more friction to the robot and makes it able to move on an even surface also. Wall pressed robots are design to climb vertical and inclined pipe lines of rough interiors. Without wheel type robots can be classified in to three categories i.e. inchworm type robot [11,12] which have inch worm type motion in pipe line with the help of two clamping and one elastic module. Snake type robot [13,14] have number of articulated active modules and Leg type robot [15,16] is able to climb vertical and horizontal pipe line having ‘L’, ‘T’ and ‘Y’ joints.

## 2. Comparison of IPIRs

Comparison of different type of in pipe inspection robots on the basis of different performance indicator (design issues) have been done to find the suitable motion mechanism of robot for same working conditions. The comparison is shown in Table 1.

Table 1. Comparison of different types of robot

Performance indicator	Wheel type robot			Caterpillar type robot		Without Wheel Type Robot		
	Wheel type robot (Simple structure)	Wheel type (wall pressed type)	Screw drive type robot	Caterpillar Robot (simple structure type)	Caterpillar Robot (wall pressed type)	Leg type robot	Inchworm type robot	Snake type robot
Vertical Mobility	Poor	Very Good	Very Good	Fair	Very Good	Very Good	Fair	Fair
Steerability	Very Good	Fair	Fair	Fair	Fair	Very Good	Fair	Fair
Size and shape adaptability	Poor	Very Good	Fair	Poor	Very Good	Very Good	Fair	Very Good
Flexibility of body	Rigid	Rigid	Less flexible	Rigid	Rigid	Rigid	Flexible	Flexible
Stability of robot	Poor	Very Good	Very Good	Fair	Fair	Fair	Fair	Fair
Moztion efficiency	Fair	Fair	Very Good	Fair	Very Good	Very Good	Very Good	Fair
Number of actuators	Fair	Fair	Less	Less	Less	More	More	More
Wireless control	Fair	Very Good	Fair	Fair	Fair	Poor	Poor	Poor

On the basis of table 1 it can be concluded that the screw type mechanism is a better choice as compared to other. So screw type mechanism has been chosen to develop new in-pipe inspection robot.

## 3. Proposed IPIR Model

New model of IPIR is based on screw drive mechanism of locomotion it have two main parts, a rotor and a stator, trajectory of wheels of rotor and velocity of robot which depends on the wheel tilt angle can be expressed by the kinematic equations of the proposed robot.

### 3.1. Kinematics of screw drive type robot

Single actuator is used in screw drive type mechanism of robot so it has only one degree of freedom. The mobility of robot is generated by the motor, tilted wheels and the supporting springs on each unit. The helical motion of screw drive type robot in pipeline depends on the inner shape of pipe line. Pitch of the robot depends on the wheel tilt angle of rotor. Following assumptions are taken to drive the kinematics of a screw drive type robot-

- All wheels are in contact with the inner surface of the pipe.
- Telescopic arms are friction less.
- Friction between wheel and hub is negligible.
- Transmission loss between motor to rotor is zero.
- Pipe wall is non-deformable.
- Wheel tilt angle is constant during the motion of robot.

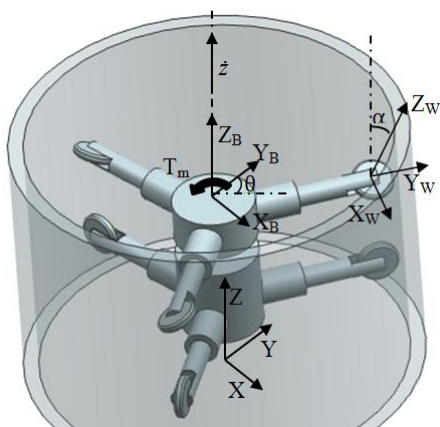


Fig.2. Motion of screw drive type robot inside the pipe line

Referring to Figure 2, if  $d\theta$  is the angular displacement of the rotor of robot,  $d\phi$  is the angular displacement of wheel and  $\alpha$  is the wheel tilt angle then displacement of the rotor about Z axis is expressed as

$$dz = (b + r)d\phi \tan(\alpha) ; \quad \alpha \neq \frac{\pi}{2} \tag{1}$$

Where b is the length of elastic arm and r is the radius of wheel.

If  $R$  denotes the radius vector on the circular plate which is equal to internal radius of the pipe.  $H$  denote a position vector of helical motion of robot from the origin under the global coordinate system inside the straight pipe line. Then the Radius  $R$  vector can be expressed as-

$$R = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} R \cos \theta \\ R \sin \theta \\ 0 \end{pmatrix} \tag{2}$$

Tilted wheels are mounted on the rotor with an inclination angle  $\alpha$ . When rotor rotates around the z axis the wheels proceed on the inner surface of the pipe following a helical path. Due to the motion of tilted wheel on the helical path, rotor gets linear movement along the z-axis. Therefore the rotation of these wheels in pipe realizes a screw driving mechanism. Transformation of robot along z axis  $T_z$  can be represented as follows:

$$Tz = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & R\theta \tan \alpha \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3)$$

The vector  $Hs$  of a point on the helix is calculated as:

$$\begin{pmatrix} Hs \\ 1 \end{pmatrix} = Tz \begin{pmatrix} R \\ 1 \end{pmatrix} = \begin{pmatrix} R \cos \theta \\ R \sin \theta \\ R\theta \tan \alpha \\ 1 \end{pmatrix} \quad (4)$$

Trajectory of the rotor moving along z-axis in a straight pipe ( $Hs$ ) with wheel tilt angle  $18^\circ$  and pipe diameter 152 mm is shown in Figure 3 below.

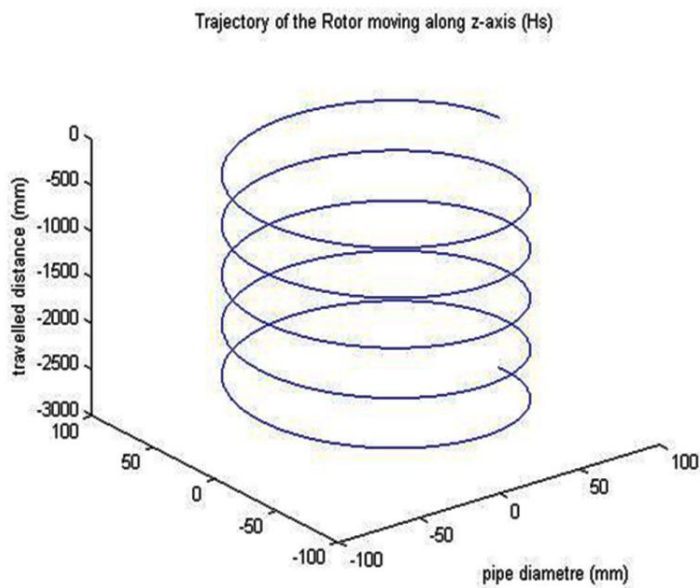


Figure 3 Trajectory of the rotor moving along z-axis in a straight pipe

The position vector of helical motion in curved path  $H_c$  can be expressed as follows:

$$\begin{pmatrix} H_c \\ 1 \end{pmatrix} = \begin{pmatrix} (R_c + R \cos \theta) \cos\left(\frac{R\theta \tan \alpha}{R_c}\right) \\ R \sin \theta \\ (R_c + R \cos \theta) \sin\left(\frac{R\theta \tan \alpha}{R_c}\right) \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} H_c \\ 1 \end{pmatrix} = \begin{pmatrix} (R_c + R \cos \theta) \cos K\theta \\ R \sin \theta \\ (R_c + R \cos \theta) \sin K\theta \\ 1 \end{pmatrix}$$

(5)

Where  $K = \frac{R \tan \alpha}{R_c}$

$R_c$  represents the radius of curvature of curved pipe and  $R$  is the radius of pipe. The trajectory of the rotor wheel can be plotted with the help of Matlab. Plot for  $R_c=152\text{mm}$ ,  $R=76\text{mm}$  using equation (5) with is depicted in Figure 4.

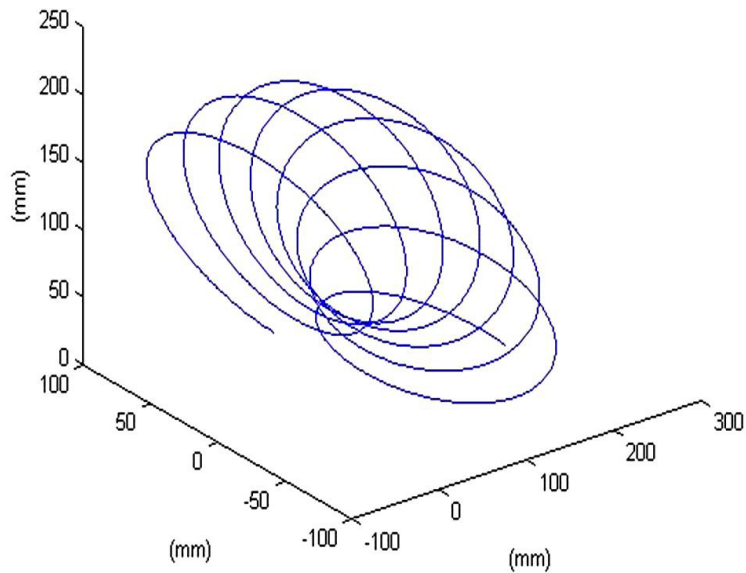


Fig.4. Trajectory of the rotor wheels moving in a curved pipe

### 3.2. Dynamics of robot

Analysis for selection of spring stiffness and the motor torque is necessary to design a robot which has optimum weight and size. To ensure the capability of robot to climb the vertical pipe line it is necessary to calculate torque and minimum spring stiffness which can support the weight of robot during climbing a vertical pipe line. Figure 5 shows the three arms of the proposed model with forces at the point of contact between wheel curved surface and pipe internal curved surface.

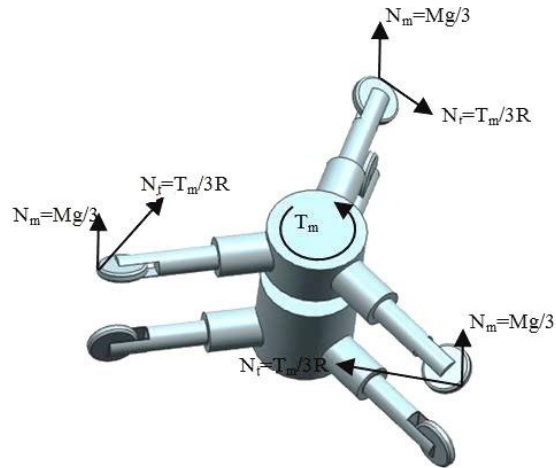


Fig.5. Forces and Torque applied on robot when it climbs the vertical pipe line

<b>Nomenclature</b>		
<b>Notation</b>	<b>Significance</b>	<b>Unit</b>
$M$	Mass of the Robot	Kg
$g$	Gravitational acceleration =9.81	m/sec <sup>2</sup>
$T_m$	Torque produce by Motor	mNm
$T_w$	Torque on wheel	mNm
$N_t$	Fore on pipe wall produce by motor torque	N
$N_m$	Force on pipe interior due to gravity	N
$\alpha$	Wheel tilt angle	Degree
$f$	Static friction force	N
$\mu$	Coefficient of friction between wheel and pipe interior	-
$R$	Radius of pipe	Mm
$M_{hull}$	Mass of hull	Kg
$M_{motor}$	Mass of motor	Kg
$m$	Mass of wheel	Kg
$b$	Distance from centre of hull to the central axis of wheel	M
$r$	Wheel radius	M
$A$	Effective cross-sectional area of Robot	m <sup>2</sup>
$C_{drag}$	Coefficient of Drag	----
$R$	Motor Resistance	$\Omega$
$L$	Motor Inductance	H
$I_{hp}$	Polar Moment of Inertia of Rotor	Kg.m <sup>2</sup>
$I_{wx}$	Wheel Moment of Inertia about x-axis	Kg.m <sup>2</sup>
$I_{wz}$	Wheel Moment of Inertia about z-axis	Kg.m <sup>2</sup>
$I_m$	Motor Moment of Inertia	Kg.m <sup>2</sup>
$\mu$	Fluid Dynamic Viscosity	Kg/m.s
$v$	Downward Velocity of the Fluid	m/sec
$\rho$	Fluid Density	Kg/m <sup>3</sup>
$g$	Gravitational Acceleration	m/sce <sup>2</sup>
$K_f$	Damping Constant	N.m.s
$K_m$	Torque Constant	N.m/A

Focusing on one driving arm, the wheel torque  $T_w$  to enable the robot to climb up in straight pipe is obtained as:

$$N_t \cos \alpha \geq N_m \sin \alpha \tag{6}$$

The static friction force  $f$  depends on the normal force  $F_n$  on the inner wall of the pipe i.e. the force due to the spring and static coefficient of friction between wheel and pipe interior. In case of insufficient static friction force between pipe interior and robot wheels robot may slip downwards even with positive torque. Therefore the necessary condition for robot stability is as follows:

$$f \geq (N_t \sin \alpha + N_m \cos \alpha) \tag{7}$$

During the vertical motion of robot the force due to the spring  $F_s$  and the normal force  $F_n$  are the same. Therefore  $f$  can be written as:

$$f = \mu kd \tag{8}$$

By solving equation (6) and (7) we get the necessary condition for minimum motor torque required to climb the vertical pipe which can be expressed as

$$RMg \tan \alpha \leq T_m \leq R(3\mu kd \cos \alpha - Mg \cot \alpha) \tag{9}$$

Where:  $RMg \tan \alpha = T_{min}$

The value of motor torque ( $T_m$ ) should be greater than the minimum value of torque required ( $T_{min}$ ) to climb the pipe line. If it exceeds the maximum value of torque with respect to coefficient of friction between wheel of robot and the pipe interior then it starts slipping, hence it is necessary to achieve the value of torque within this range. In equation (9) the value of motor torque is directly proportional to coefficient of friction and spring stiffness. Hence it can be concluded that; higher motor torque will always be required for higher value of spring stiffness and higher coefficient of friction. For lower payload and/or less mass of the robot required minimum motor torque to climb the pipe line will be less.

using equation (9) a graph (Figure 6) is generated between the limiting motor torque and coefficient of friction by varying the value of spring stiffness from 0.1 to 9.8N/mm and the coefficient of friction is changed from 0 to 1.5 (to cover wide range of wheel-pipe material combination) with respect to pipe radius 76mm. The value of spring displacement ( $d$ ) is selected from following table

Table. 2. Spring specifications

Stiffness of spring(k) N/mm	0.1	0.3	0.5	1.0	2.0	2.9	4.9	4.9	9.8
$l_{max}$ (mm)	10	10	10	10	10	10	10	10	10
$l_{min}$ (mm)	2.5	4.0	5.5	6.0	6.0	6.5	7.5	7.5	7.5
$d$	3.75	3	2.25	2	2	1.75	1.25	1.25	1.25



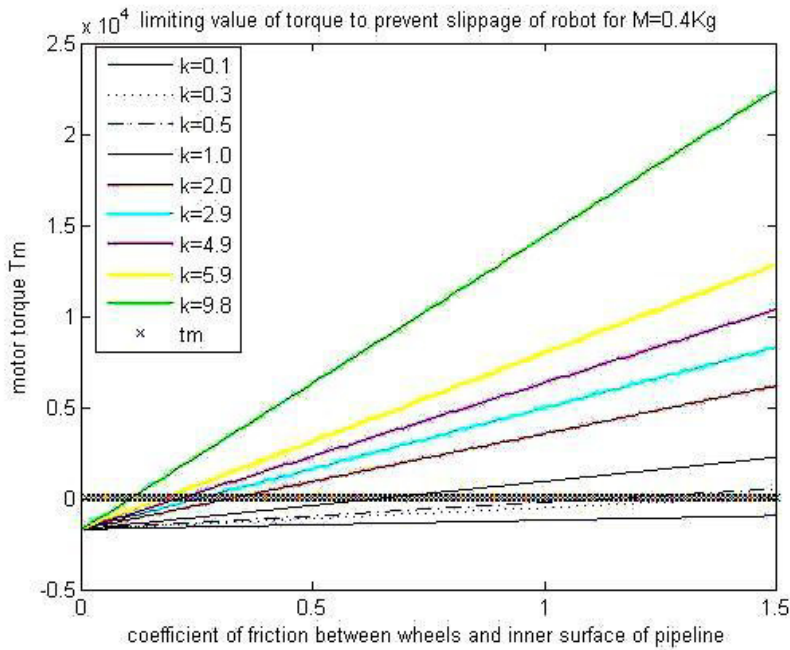


Fig.6. Limiting value of torque to prevent slippage

Motor for the robot has been chosen on the bases of the minimum required torque to climb a vertical pipe line. Motor torque also helps to design the motor shaft and coupling to transmit the torque. Governing dynamic equation of motion of the robot inside the pipeline can be expressed as follows:

$$\ddot{\theta} = \frac{T_m - b \sin \alpha \frac{\rho C_{drag} A}{2} \left\{ (b+r) \dot{\theta} \sin(\alpha) + v \right\}^2 - n \mu b F_n - (M_{Motor} + M_{Rotor} + nm)(b+r) g \tan(\alpha)}{\left( M_{motor} + M_{Rotor} + nm + n \frac{I_{wx}}{r^2} \right) \left( (b+r) \tan(\alpha) \right)^2 + \left( m + \frac{I_{wz}}{r^2} \right) nb^2 + I_{hp}} \tag{10}$$

From equation (10) it can be conclude that the governing parameters for the robot motion are wheel tilt angle ( $\alpha$ ), the normal force applied on the pipe interior by the wheels due to spring stiffness of telescopic arm  $F_n$  and the torque applied on the wheels actuators  $T_m$ , the only control input that can vary on fly is motor torque  $T_m$ .

### 3.3. Solid Model of new IPIR

Solid model of new in-pipe inspection robot has been developed with the help of Unigraphics (NX-7.5) software as shown in Figure 7. Solid model of robot consists of two parts i.e. rotor and stator. Rotor has three wheels inclined at an angle of 18°. Wheels of rotor are mounted on the two elastic arms. Springs of 0.1 N/mm stiffness are used to provide the wall press force and adaptability to the arms. Elastic arms make the robot adaptable and also make it able to move in vertical and inclined pipes. Rotor is directly connected to a motor with the help of flexible coupling which ensure the transition of torque even in inclined positions. A universal coupling can also be used for this purpose. The motor torque can be varied with respect to voltage supplied to the motor. Variable torque of motor ensures the stability of robot in case of varying cross-section of pipeline. Stator composed of motor housing, steering mechanism, wireless communication & control unit and power module. Stator has three straight wheels on the periphery which provide the stability to the robot. Wheels of the robot are composed of PVC hub with rubber tyres to ensure high frictional force and better grip between the wheels and pipe interior.

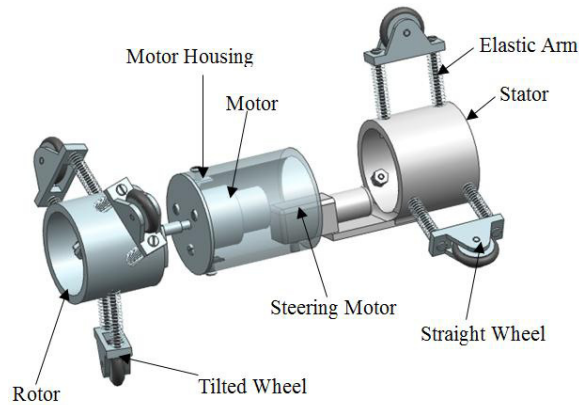


Fig.7. Solid model of new in-pipe inspection robot

### 3.4. First prototype of new IPIR

An initial prototype shown in Figure 8 has been developed to analyse the motion and working of the robot inside the pipe line. It is composed of a stator and rotor with wheels mounted on elastic arms.



Fig.8. Rough prototype of new in-pipe inspection robot

## 4. Conclusion

Based on the literature reviewed it is concluded that screw type In-pipe inspection robotic mechanism has many advantages as compared to other mechanisms. In view of this a Screw type In-pipe inspection robot has been designed in this work to perform inspection related activities inside a pipe of diameters ranging from 127mm to 152mm. Kinematic and dynamic analyses are performed to understand the behavior of the proposed model in vertical, inclined and horizontal pipe line with Y or L bends. After getting the basic dimensions from these kinematic and dynamic equations, a solid model is developed in UGNX and after some trials the basic design is finalized and presented in this work. To validate the behavior and desired outcomes an initial prototype is also developed. The developed prototype is tested in different situations and it is found that the velocity and other behaviors are in good match with our mathematical model.

## References

- [1] M. F. Yusoff , B.S.K.K. Ibrahim, H. Hamzah and H.A. Kadir, Development of Air Conditional Route Wireless Inspection Robot, International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012), pp 874-880.
- [2] Md Raziq Asyraf Md Zin, Khairul Salleh Mohamed Sahari, Juniza Md Saad, Adzly Anuar, and Abd Talip Zulkarnain, Development of a Low Cost Small Sized In-Pipe Robot International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012), pp 1469-1475.
- [3] Dongwoo Lee, Jungwan Park, Dongjun Hyun, GyungHwan Yook and Hyun-seok Yang, Novel mechanisms and simple locomotion strategies for an in-pipe robot that can inspect various pipe types, Mechanism and Machine Theory 56 (2012), pp 52-68.
- [4] Atul Gargade, Dhanraj Tambuskar and Gajanan Thokal, Modeling and Analysis of Pipe Inspection Robot, International Journal of Emerging Technology and Advanced Engineering, Volume 3, Issue 5, May 2013, pp 120-126.
- [5] Peng Li, Shugen Ma, Bin Li, Yuechao Wang, Development of an Adaptive Mobile Robot for In-Pipe Inspection Task, Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation August 5 - 8, 2007, Harbin, China pp 3622- 3627.
- [6] Taiki Nishimura, Atsushi Kakogawa and Shugen Ma, Pathway Selection Mechanism of a Screw Drive In-pipe Robot in T-branches, 8th IEEE International Conference on Automation Science and Engineering August 20-24, 2012, Seoul, Korea, pp 612-617.
- [7] Josep M. Mirats Tur and William Garthwaite, Robotic devices for water main in-pipe inspection a survey, Journal of Field Robotics, 27(4), pp. 491-508, 2010.
- [8] Kosuke Nagaya, Tomohiko Yoshino, Makoto Katayama, Iwanori Murakami, and Yoshinori Ando, Wireless Piping Inspection Vehicle Using Magnetic Adsorption Force IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 17, NO. 3, JUNE 2012, pp 474-479.
- [9] Majid M. Moghaddam, Mohammadreza Arbabtafi and A. Hadi. In-pipe Inspection Crawler Adaptable to The Pipe Interior Diameter. International Journal of Robotics and Automation, Vol. 26, No. 2, 2011, pp 135-145.
- [10] Young-Sik Kwon, Byung-Ju Yi, Design and Motion Planning of a Two-Module Collaborative Indoor Pipeline Inspection Robot, IEEE, 2012, pp. 1-16.
- [11] Megumi Ikeuchi, Taro Nakamura, and Dai Matsubara, Development of an In-pipe Inspection Robot for Narrow Pipes and Elbows using Pneumatic Artificial Muscles, 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems October 7-12, 2012. Vilamoura, Algarve, Portugal, pp 926-931.
- [12] Jinwei Qiao, Jianzhong Shang, and Andrew Goldenberg, Development of Inchworm In-Pipe Robot Based on Self-Locking Mechanism, IEEE/ASME Transactions On Mechatronics, Vol. 18, No. 2, April 2013 799, pp 799-806.
- [13] Shuichi Wmmoto, Jun Nakajim, Masanori Takata Takefumi Kanda and Koichi Suzwori, A Micro Snake-like Robot for Small Pipe Inspection, 2003 International Symposium on Micromechatronics and rIUMAh SCIENCE, 2003, pp 303-308.
- [14] Sigurd A. Fjerdigen, Pal Liljeback and Aksel A. Transeth A snake-like robot for internal inspection of complex pipe structures (PIKo), The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems October 11-15, 2009 St. Louis, USA, pp 5665-5671.
- [15] Robin Bardbeer, stephen Harrold, Frank Nickols and Lam F Yeung, An underwater robot for pipe inspection, IEEE transactions, 1997, 152-156.
- [16] Andreas Zagler and Friedrich Pfeiffer, "MORITZ" a Pipe Crawler for Tube Junctions, Proceedings of the 2003 IEEE International conference on Robotics & Automation Taipei, Taiwan, September 14-19, 2003, pp 2954- 2959.