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Design and development of cam-operated in-pipe robot (CIPR)

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Keywords

In-pipe robot;
Three-lobed cam;
Cam-operated;
Dynamic model;
Simulation.

Abstract

This paper presented a novel mechanism and dynamic model of Cam-operated In-Pipe Robot (CIPR) as a proof of concept. The CIPR would be useful for in-pipe inspection for detecting the defects like cracks, surface wear, damage, scaling etc. Based on the dynamic model, a gripping mechanism actuated by a three-lobed cam has been developed. A special three-lobed cam provides sufficient frictional force to maneuver and stop the robot inside the pipe of diameter 250 mm during inspection and cleaning task. A proposed dynamic model determines the frictional force and torque required to move the robot. A specially designed three-lobed cam makes the overall mechanism compact as compared to available in-pipe robots. A single cam is adequate to exert uniform gripping force between the contact surface of the wheel and the inner surface of the pipe. In the present work, solid model of the CIPR is used to analyze and simulate the dynamics of the CIPR using ADAMS. The model is tested in simulated environment for vertical motion to determine the frictional force and wheel torque characteristics. The simulation results are in line with the analytical results. Further, the prototype is successfully maneuvering inside the pipe for different orientations.

1. Introduction

Pipelines have prime importance for the smooth functioning of many industrial operations and hence it is necessary to prevent the damages of pipelines caused by natural adversity, chemical rusting and aging. The health of the pipeline can be maintained by active monitoring and frequent inspections. Monitoring and inspection of pipelines are difficult due to narrow working space, complicated structure, hazardous environment as well as it is located underground which prevent easy access to humans. Therefore in-pipe robot is one of the best alternatives for inspection and fault-detection of pipelines.

1.1. Existing in-pipe robots

Based upon manoeuvring mechanisms, in-pipe robots are classified as active locomotion and passive locomotion. Active locomotion type in-pipe robots are preferred as they offer better control on speed and the direction inside the pipe. Active locomotion in-pipe robots are further classified into various categories i.e. wheeled, caterpillar, snake, legged, inchworm type, and Pipe Inspection Gauge (PIG) type robots. Wheeled type in-pipe robots are classified as simple structure type, wall pressed type, screw drive type. Wall pressed wheeled type robot has large traction force and better climbing capability as compared to simple structure wheel type robot [1,2]. Caterpillar type robot has no ability to climb and bigger in size, snake type robot has complex in structure and difficult to control, legged type robot has complex in structure and needs more actuator, inchworm type robots are simple in structure but lower speed mobility whereas PIG type robots have uncontrolled motion state as its motion depends on the flowing medium inside the pipe [3]. Various in-pipe robots are developed by researchers for numerous applications based on different mechanisms. A caterpillar type in-pipe robot has been developed to inspect the long-distance pipeline [4]. A screw drive type in-pipe robot has been designed to climb through horizontal and vertical sections of pipe with large payload [5]. A snake type in-pipe robot (Slyder) has been developed to check the blockages

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inside the pipelines. This robot utilizes a crawling and slithering movement patterns to move effectively [6]. Leg type robot has been developed for the inspection of pipe with varying diameter. This robot consists of three legs actuated with a parallelogram linkage mechanism [7]. A flexible squirm pipe robot consisting of flexible axle and self-steering device has been developed to achieve the peristaltic motion and to develop self-steering capability [8]. Earthworm type mobile inspection robot has been developed to transverse in a long pipe having 8 elbows and 79 mm inner diameter [9].

The manoeuvring capability of pressed type wheeled robot depends on the gripping mechanism to create sufficient friction force between the wheel and pipe surface to avoid slippage. The in-pipe robot has to move through various sections of pipe i.e, vertical, inclined, bend, *T* and horizontal to perform the task. Motion through the horizontal section is found to be easy as compared to the other sections. Researchers have developed various pressed type wheel robots for numerous applications. Pipeline inspection robot with two-wheel chains has been developed to allow simple robot control and easy user interface, especially at T-branch [10]. The development of an intelligent plugging robot equipped with an over-line and universal shaft connector featuring a hollow double-ball hinged structure is a noteworthy innovation aimed at enhancing trafficability and reliability in the elbow sections of pipelines. This design offers solutions to common challenges encountered in conventional steering equipment when navigating through pipeline bends [11]. An in-pipe cleaning robot with the 6-link sliding mechanism has been developed which can be adjusted to fit into the inner face of pipe using pneumatic pressure [12]. Mobile robot for pipeline exploration utilizing magnetic wheels for vertical travel has been developed for the inspection of pipelines [13]. The MRINSPECT series in-pipe robots have been developed for various applications. It is based on a multi-axial differential gear mechanism to provide traction forces to the robot. The major concept of the MRINSPECT series is the differential drive which can drive through a curved pipe, branch pipes and straight pipes of diameter 150 mm to 200 mm by controlling the speed of each driving wheel [14,15]. A mobile robot has been developed for inspecting oil pipelines composed of six groups of symmetrical supporting wheels with an advanced control system [16]. A miniature robot for inspecting the inner walls of pipes was designed that can be adaptable in vertical, inclined, and bent paths. The proposed mechanism was based on shape memory alloy actuators to adjust the contact force between the robot and the inner wall of the pipe [17]. The structure of the inchworm in-pipe robot has been developed which can adapt to the diameter of 140–180 mm pipe by including a self-locking mechanism and telescopic mechanism. The proposed telescopic mechanism claims that the robot's propulsion speed is twice with the same power as compared to a traditional robot with a telescopic mechanism [18]. To navigate a robot inside a pipe of varying diameter and section, it is necessary to adapt itself to the size of the pipe. A reconfigurable field robot has been developed to move inside circular and rectangular section pipes by incorporating the mechanism that permit it to adjust its width and height and shift its Centre of Mass (COM) to adapt a robot as per the size of the pipe [19,20]. A cornering algorithm has been presented for crawler pipeline robots with an electric telescopic rod structures for controlling the smooth and stable operation of the robot in the pipeline. It is claimed that the optimization analysis of telescopic rod expansion and the ratio of the speed of each crawler has been performed to resolve the difficulty for the robot to adapt to the change of pipe diameter automatically [21].

In light of advancements in in-pipe robot technology, these robots can be classified into three distinct generations. First generation in-pipe robots are operating in simple configurations, offering restricted motion control capabilities and primarily serves cleaning purposes. Second generation in-pipe robots are capable to move through curved section of pipe and can control remotely and mainly used for data gathering and inspection. Third generation in-pipe robots are capable to operate in the pipes having complex configuration and variable diameter with high motion control and is used for cleaning, inspection, real time data collection by using the various sensors [22]. Many researchers incorporated the sensing technology in the in-pipe robot to improve the overall performance of the inspection and cleaning task. Navigating the in-pipe robot through elbow section of pipe with an unknown direction and angle is one of the challenging tasks. This has been overcome by implementing autonomous elbow controller for differential drive. The controller utilizes three low-cost feeler sensors to navigate the FURO II robot around 150 mm short elbows [23]. Navigating a robot inside small-diameter pipes while dealing with communication and power cables can indeed be a challenging operation. A "Smart Crawler" an integrated wireless robotic system has been developed for Water Distribution Systems (WDS). Further, the synchronized two-phase motion controller and the wireless sensor module has been incorporated to provide consistent motion in complex configurations of WDS and wireless data transmission to resolve the issue of weakening signal [24]. A train-like in-pipe robot was proposed for the visual inspection of ferromagnetic pipes. The robot equipped with omnidirectional wheels to provide longitudinal and lateral movements. For adhesion between the robot and the pipes, permanent magnets have been used. To control the robot's movement inside a pipe, visual control panels were used to observe the inspection area in real-time through the front and rear cameras. The robot was also equipped with temperature and humidity sensors to provide the real-time monitoring of the pipe's internal conditions. [25].

The manoeuvring of in-pipe robot through bend and T-section of pipe is comparatively difficult as compared to straight pipe. This issue can be resolved by designing a compact mechanism. The compactness of mechanism is mainly depending on the length to diameter ratio of robot. Table 1 compares the length to diameter ration along with other design parameters of various existing robot with CIPR.

Table 1. Comparison of CIPR with existing robots.

	[26]	[27]	[28]	[29]	[30]	CIPR
Type of robot	Wheeled	Wheeled	Inchworm	Inchworm	Inchworm	Wheeled
Average robot length (mm)	137	260	178	--	300	130
Inside pipe diameter (mm)	175	200	16	---	390	250
Length to diameter ratio	0.78	1.3	11.12	>1	0.76	**0.52**
Adhesion method	Active	Passive	Passive	Active	Active	Active
Number of actuators	2	1	1	3	1	3 + 1*
Maneuvering direction	Two-way	Two-way	One-way	Two-way	Two-way	Two-way

* 3 actuators for maneuvering and 1 for switching between mode-I and mode-II

1.2. Issues in existing robots and motivation for the present work

In this section, various issues with the existing in-pipe robots have been reported.

The key issues associated with the existing systems are identified and discussed below:

- Wheeled type robots are simple in structure, steerable and suitable for smooth surfaces as they are unable to climb over obstacles;
- Caterpillar type robots can travel on an uneven surface and easily overcome obstacles. Snake robots are complex in structure, require more actuators and hence comparatively difficult to control;
- Legged/walking robots have a complex mechanism for locomotion and might get stuck if there is a hole inside the pipe. However, they can adapt to various pipe diameters and have edge over wheeled and caterpillar type robots in branched pipes;
- Inchworm type robots offer better movement in a curved pipe. They have high drag force which may damage the inner surface of the pipe and find it difficult to overcome bends. Wall-pressed type robots are energy efficient and suitable for long range. It may stick if there is a hole inside the pipe; however, this issue can be resolved by proving tracks;
- Telescopic type in pipe robots has a larger length to diameter ratio. It uses the hydraulic system for continuous propulsion. Telescopic robots require more space for the installation of the actuators and demand complex control methods.

Every robot might not be equally suitable for similar applications as it is developed according to specific design requirements. Therefore, the development of in-pipe robots to satisfy all parameters is still a challenge for the research community and hence in-pipe robots are always designed with certain limitations. Existing robots require more space to accommodate the linkages and installation of actuators which makes the design complex. On the other hand, the proposed CIPR uses a single cam to actuate all three identical gripping elements and has a minimum length to diameter ratio which offers a compact design with better control.

2. Mechanism design of the robot

2.1. Gripping module mechanism

The solid model of the proposed gripping mechanism of CIPR is shown in Figure 1. It consists of three identical elements arranged radially at an angle of 120º. A complete gripping system is fitted on the mounting plate. In order to facilitate linear movement of the gripping system, trapezoidal guideways are provided on the mounting plate

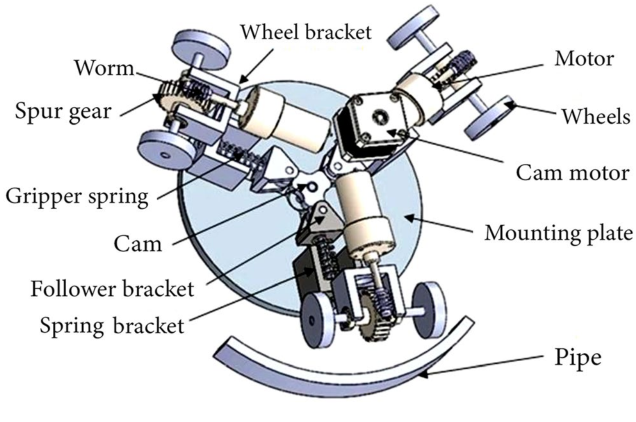

Figure 1. Solid model of Gripping module.

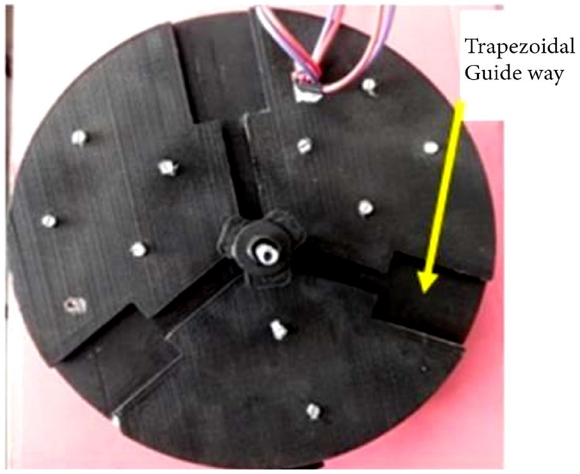

Figure 2. Mounting plate with trapezoidal guide-way.

as shown in Figure 2. The centrally mounted three-lobed cam acts as a driver actuated by the stepper motor. During the operation, the required gripping force is transmitted from cam to wheels sequentially as shown in Figure 3.

CIPR has to stop in between to perform inspection task that is achieved by rotating the cam to its maximum lift. This rotational motion of the cam pushes the follower bracket through the roller follower. The compression action of the gripping spring pushes the spring bracket which results in the movement of wheel bracket and the wheels towards the surface of the pipe. To manoeuvre the CIPR inside the pipe, the cam is rotated till the follower reaches the lowest position of the cam which pushes back all the elements of the gripping system by the lift of the cam. The sufficient torque is transmitted to the wheels by DC motors through worm and worm-wheel type gearing system.

Figure 3. Gripping force transmission sequence.

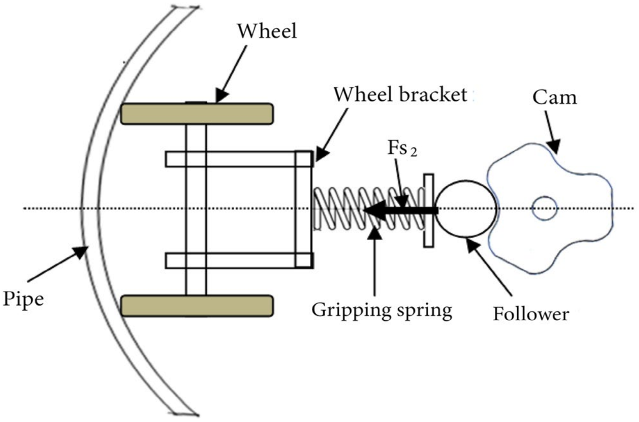

Figure 4. Position of cam during motion i.e., mode-I.

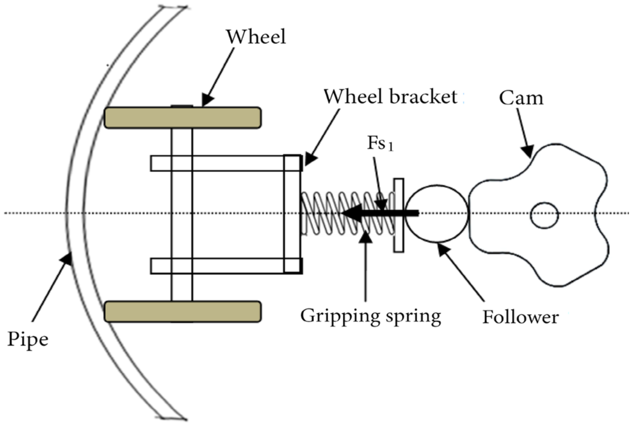

Figure 5. Position of cam during mode-II.

2.2. *Working principle*

In the proposed design, a three-lobed cam has been used to assist the locomotion of the in-pipe robot. During the operation, the robot needs to move inside the pipe and stop at a particular location for inspection. To achieve this, the robot operates in two modes i.e., mode-I and mode-II as shown in Figures 4 and 5. In mode-I (Figure 4), the follower will be at the lowest position of the cam which offers sufficient grip between the wheels and the pipe surface. This position ensures the continuous contact of the wheels through spring force with the inner wall throughout the motion. The mode-II (Figure 5) corresponds to the maximum lift position which allows the robot to stop in between as per the need.

3. Dynamic model

A dynamic model is developed to find the required torque at the wheel to move the robot inside the pipe. The gripping module consists of six wheels and therefore there are six contact (gripping) points. For generalizing the equation, assume the number of contact surfaces is n. So, the friction force (F_{r1}) at each wheel at rest position (mode-II) to avoid the slip of robot is given by Eq. (1):

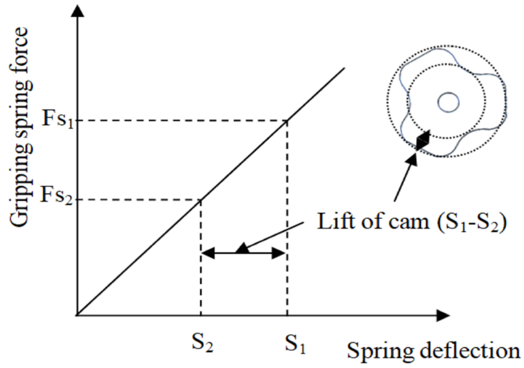

Figure 6. Plot for gripping force versus Spring deflection.

$$F_{r1} \geq \frac{W}{n}, \tag{1}$$

where W is weight of gripping module.

The normal gripping spring force required at each wheel to develop a sufficient friction force to keep the system at rest position is expressed in Eqs. (2) and (3).

$$F_{r1} \geq \mu \times F_{s1}, \tag{2}$$

$$F_{r1} \geq \mu \times k_1 \times S_1, \tag{3}$$

where μ is coefficient of friction between rubber wheel and inner surface of acrylic pipe, Fs_1 is the normal gripping spring force at rest position i.e., mode-II, k_1 is the stiffness of gripping spring and S_1 is the deflection of gripping spring at rest position i.e., mode-II.

Normal gripping spring force during the motion i.e., mode-I (Fs_2) is assumed to be 80% of the normal gripping spring force needed to keep the system at rest position i.e., mode-II.

To operate the robot during mode-I and mode-II, a special three-lobed cam is designed. A suitable lift is provided to the camas shown in Figure 6 which is responsible to apply sufficient normal gripping force during both modes.

The lift of the cam is equal to the difference of deflection of the gripping spring during mode-I and mode-II. Based on the lift of the cam and magnitude of gripping force, suitable standard spring LC045F10 series [31] is selected.

The torque required to overcome the friction to accelerate the ith wheel is given by Eq. (4):

$$T_i = F_t \times r_w, \tag{4}$$

where T_i is the torque developed at each wheel, F_t is the tractive force and r_w is the wheel radius.

A resistive force as shown in Figure 7, developed at each wheel is equal to the tractive force (F_t) and expressed in Eq. (5):

$$F_t = \frac{W \times \sin(\alpha)}{n} \pm F_{r2}, \tag{5}$$

where α is the angle between the line of action of W and the

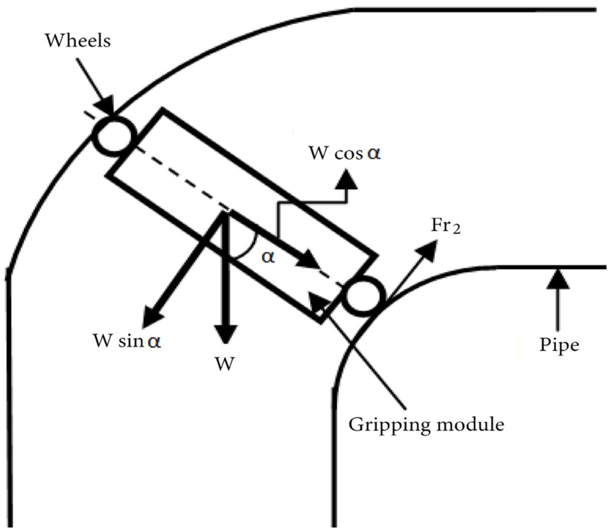

Figure 7. Free body diagram of gripping module during mode-I.

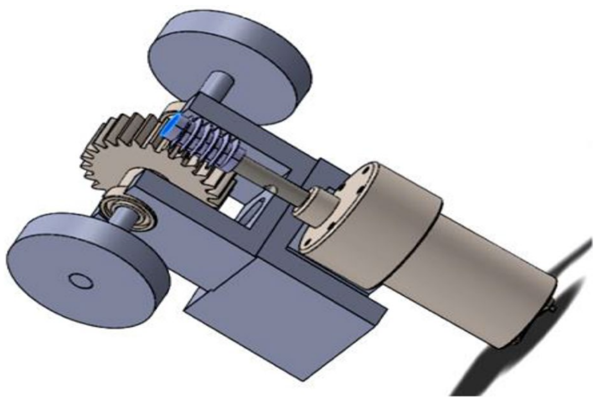

Figure 8. Transmission system.

plane of gripping module plate. '+' sign indicate the upward motion and '−' sign indicate the downward motion of robot. Friction force developed at each wheel during mode-I:

$$F_{r2} = \mu \left\{ k_1 \times S_2 + \frac{W \times \cos(\alpha)}{n} \right\}, \tag{6}$$

where S_2 is the deflection of gripping spring during mode-I.

Tractive force developed at wheel surface after substituting Eq. (6) in Eq. (5) will be as given in Eq. (7):

$$F_t = \frac{W \times \sin(\alpha)}{n} + \mu \times \left\{ k_1 \times S_2 + \frac{W \times \cos(\alpha)}{n} \right\}. \tag{7}$$

Hence, the expression for torque required at *i*th wheel is written as Eq. (8):

$$T_i = \left[\frac{W \times \sin(\alpha)}{n} + \mu \times \left\{ k_1 * S_2 + \frac{W \times \cos(\alpha)}{n} \right\} \right] \times r_w. \tag{8}$$

The gripping system consists of two wheels to transmit the torque for the motion. The worm wheel is mounted on the wheel shaft itself as shown in Figure 8. The wheel received the required torque through the worm driven by a DC motor. Therefore, torque required at the motor shaft is determined as per Eq. (9):

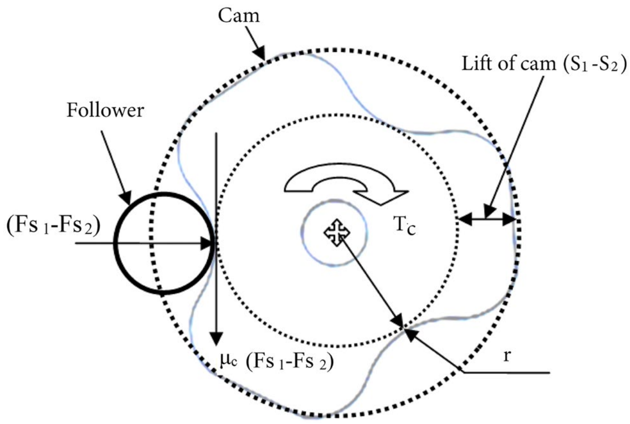

Figure 9. Force analysis of CAM.

$$T_m = \frac{2 \times \left[\frac{W \times \sin(\alpha)}{n} + \mu \times \left\{ k_1 \times S_2 + \frac{W \times \cos(\alpha)}{n} \right\} \right] \times r_w}{\frac{Z_1}{Z_2} \times \eta}, \tag{9}$$

where T_m is the Motor torque, Z_1 is the number of teeth on worm wheel, Z_2 is the number of starts of worm and η is the machine efficiency. Eq. (9) is used to select the suitable motor to drive the in-pipe robot.

The torque (T_c) required to rotate the cam [32] from mode-I to mode-II is given by Eq. (10). Force acting on the cam and follower is shown in Figure 9. The torque obtained from the following equation is used to select the stepper motor to drive the cam:

$$T_c = \mu_c \times (Fs_1 - Fs_2) \times [r + (S_1 - S_2)], \tag{10}$$

where T_c is the torque required to actuate the cam from mode-I to mode-II and vice-versa, μ_c is the coefficient of friction between cam and follower and *r* is the radius of cam base circle. The pressure angle is an essential parameter in cam and follower mechanisms for several reasons such as the smooth and efficient motion transmission, minimizing wear and friction, noise reduction, etc. The pressure angle of the three-lobed cam used in CIPR is calculated by graphical method and it is in the range of 5° to 28°.

4. Prototype exploration

To confirm the effectiveness of the developed dynamic model expressed in Eq. (8), the experiment has been carried out by manoeuvring the CIPR inside the acrylic pipe. The prototype to perform the test is shown in Figure 10. The acrylic pipe of a diameter of 250 mm has been used for testing to visualize the operation. All the parts are 3-D printed with PLA+ material at 0.1 mm layer thickness and 100% infill. The input parameters used to perform the testing are shown in Table 2.

For the proof of concept, the prototype of CIPR has been developed as shown in Figure 11. Acrylic pipe of 250 mm diameter is employed for the motion of CIPR in the horizontal, vertical and inclined pipe. The prototype consists of a control unit, Joystick and motor unit as shown in Figures 12 and 13. In the control unit, a microcontroller ATMEGA-2560 is deployed to control the robot with help of a Joystick

Table 2. Input parameters.

Parameters	Values
Mass in-pipe robot *(M)*	5 kg
Weight of each gripping module *(W)*	49.05 N
Number of contact surfaces between wheel and pipe *(n)*	6
Radius of wheel (r_w)	0.0225 m
Deflection of gripping spring during mode-II (S_1)	28.91 mm
Deflection of gripping spring during mode-I (S_2)	23.13 mm
Coefficient of friction between rubber wheel and acrylic pipe (μ)	0.8
Stiffness of gripping spring (k_1)	1.47 N/mm
Coefficient of friction between cam and follower (μ_c)	0.2
Number of starts of worm (Z_2)	1
Number of worm gear (Z_1)	25
Machine efficiency (η)	30%
Radius of cam base circle	8.5 mm
Lift of cam	5 mm
Uncompressed length of gripper spring	57.15 mm
Diameter of gripper spring	10.67 mm
Diameter of pipe	250 mm

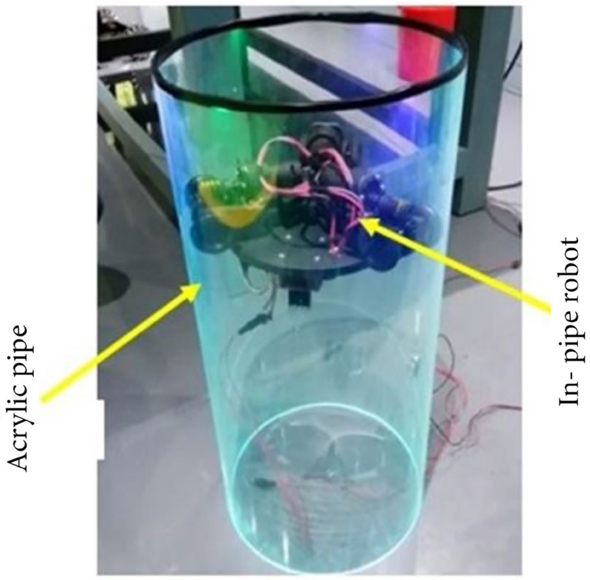

Figure 10. Demonstration of CIPR motion inside acrylic pipe.

which consists of NRF24L01 Transceiver Module. In order to drive the CIPR, DC motors are used. These motors drive through motor driver L298 which is controlled by Pulse-Width Modulation (PWM) signals generated by control units.

5. Dynamic simulation of CIPR using ADAMS

Several studies have reported the use of ADAMS software for performing dynamic simulation of various in-pipe robots [33-35]. In line with these studies, in the present work, ADAMS multibody dynamics simulation software is used to carry out the dynamic simulation of CIPR for vertically upward motion in straight pipe. The simulation was performed to validate the result of proposed dynamic model of CIPR.

A flow chart of the ADAMS dynamics simulation process is shown in Figure 14. The basic process includes CAD model generation, importing in ADAMS environment, setting of design parameters and coordinate system, selection of suitable material and assign the mass property, assign the proper joint and constraints, defining of coefficient of friction at the contact surfaces, simulation solution settings, and finally post-processing to visualize the results.

In the ADAMS simulation environment, 3 revolute pairs (Cam motor and cam, follower and follower bracket, shaft and wheel), 2 translation pair (Follower bracket and Base plate, spring bracket and Base plate) and one fixed pair between spring bracket and wheel bracket are set. The prime focus of the simulation was to find the characteristics of friction force and torque with respect to time. Figure 15 shows the CIPR in ADAMS environment.

The simulation result of friction force and torque with respect to time is discussed in subsequent section.

6. Result and discussion

The results obtained from the dynamic model and the simulation is discussed in this section. The developed dynamic model (Eq. (7)) is used to predict the manoeuvrability of the proposed CIPR. The dynamic model is capable of estimating the wheel torque and frictional force for inclination (α) ranging from 0° (horizontal) to 90° (vertical) in acrylic pipe of the inside diameter of 250 mm. The variation of wheel torque and frictional force with change in angle α based on the mathematical model is shown in Figures 16 and 17 respectively.

As shown in Figure 16, the maximum torque at wheel is developed in the bend section of pipe correspond to 52.16°. This is due to the contribution of component of the total weight of CIPR during motion in bend section. The frictional force is maximum when CIPR is moving in horizontal section of pipe as the component of weight of CIPR is contributing as a normal force along with spring force and minimum while the motion in vertical direction as shown in Figure 17.

For validating the results obtained from the dynamic model, the simulation of CIPR is performed in ADAMS simulation environment for vertical upward motion inside the acrylic pipe (angle $\alpha = 90^\circ$). The characteristic of wheel torque and frictional force with respect to time is given in Figures 18 and 19 respectively.

As seen in Figure 18, the average wheel torque obtained by simulation during vertical upward motion is found to be 0.91 N-m. Whereas, the dynamic model gives the torque of 0.8 N-m for the same motion.

The average value of frictional force during vertical upward motion is found to be 18.8 N by simulation (Figure 19). Whereas, value obtained by the dynamic model is 20.4 N.

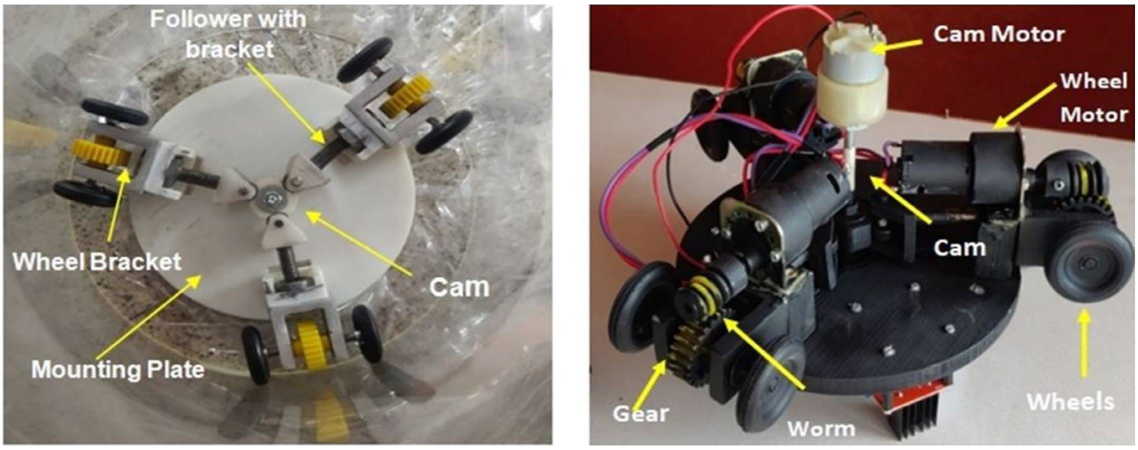

Figure 11. CIPR prototype with internal parts.

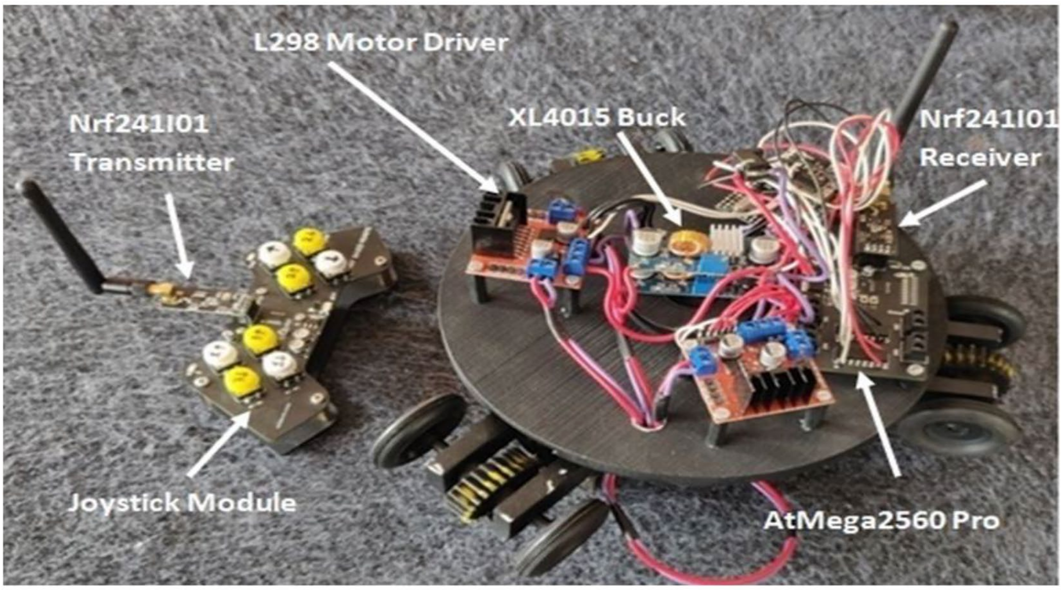

Figure 12. Prototype of CIPR with joystick.

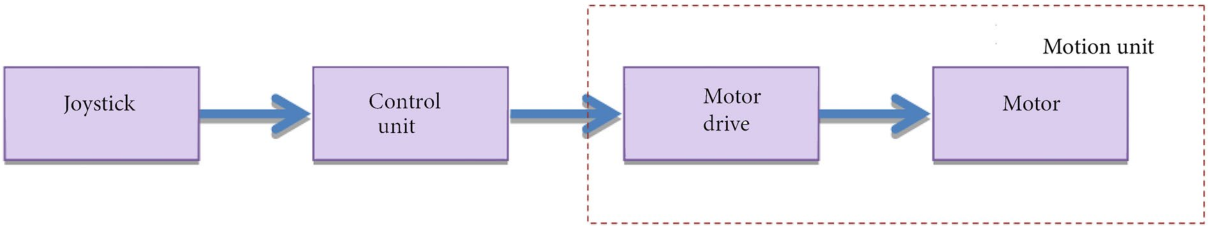

Figure 13. Robot system: Control unit, motion unit and joystick.

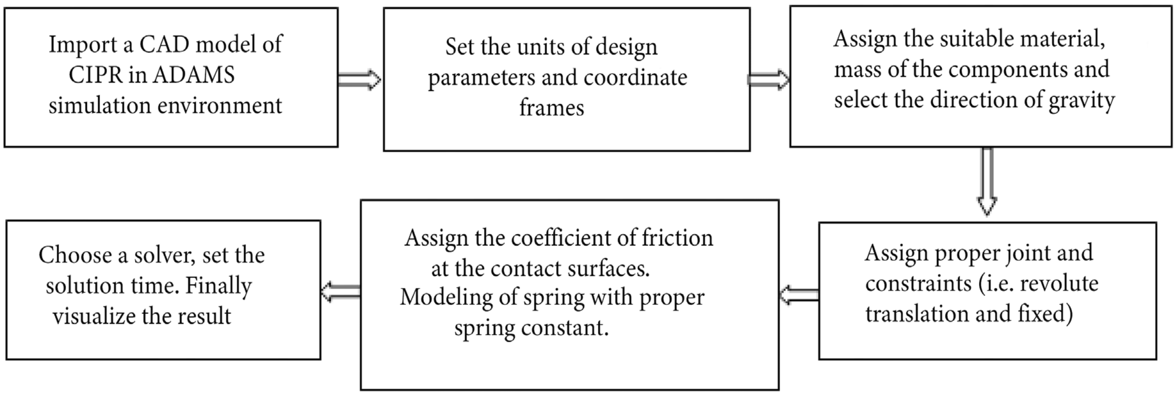

Figure 14. ADAMS dynamics simulation process.

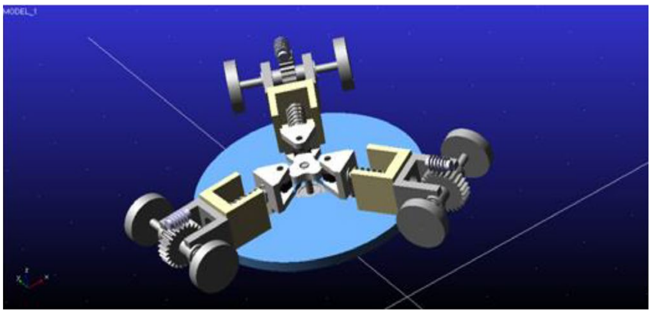

Figure 15. CIPR in ADAMS environment.

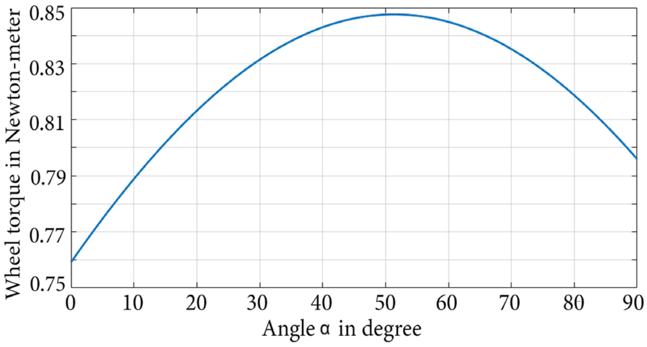

Figure 16. Variation of wheel torque with change in angle α.

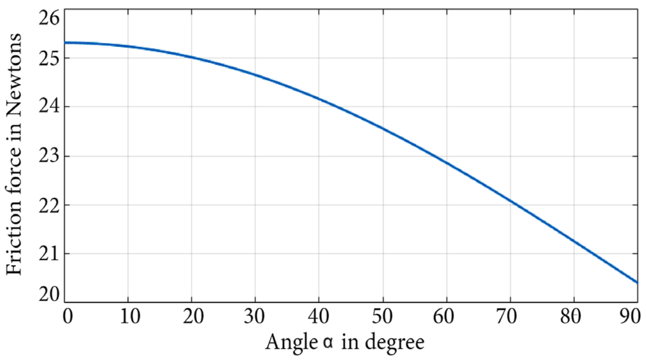

Figure 17. Variation of frictional force with change in angle α.

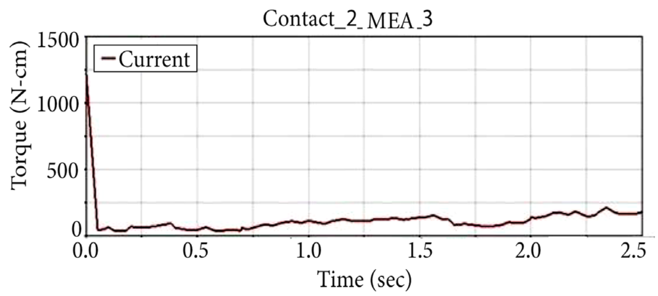

Figure 18. Simulation plot of wheel torque with respect to time.

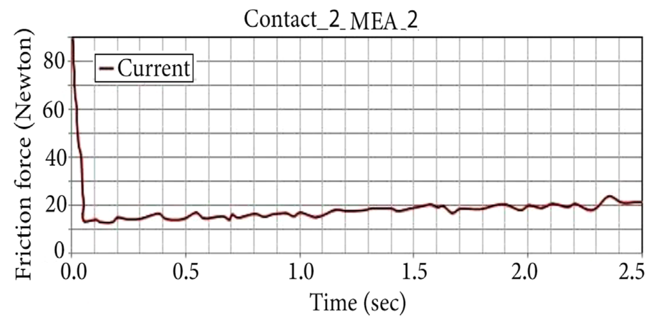

Figure 19. Simulation plot of frictional force with respect to time.

7. Conclusion

In the present work, a novel mechanism of Cam-operated In-Pipe Robot (CIPR) for pipe inspection is proposed. The three-lobed cam enables the CIPR to stop for inspection and maneuverer inside the pipe by providing the appropriate gripping forces. A dynamic model has been developed to analyse the motion and working of CIPR inside a 250 mm diameter pipe. The developed dynamic model has been used to determine the frictional forces and the torque requirement for CIPR. The dynamic simulation was performed in ADAMS software to validate the result of proposed dynamic model and it is found that there is good correlation in the result. Based on the dynamic model and subsequent simulation, a prototype of CIPR has been developed as a proof of concept for validation. The CIPR is capable of performing the defined task as predicted by both dynamic model and simulation. Moreover, CIPR has least length to diameter ratio and hence the proposed mechanism is most compact to maneuverer in bend and T-section of pipeline. The dynamic model shows the possibility of the use of CIPR in pipe bends however it is recommended to validate this claim by conducting real time tests for different environments. Furthermore, the dynamic model proposed in this work can be used for developing different in-pipe robots for various situations such as pipes of different diameters, surface conditions.

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Nomenclature

M	Mass of gripping module (kg)
W	Weight gripping module (N)
g	Gravitational acceleration (m/s^2)
n	Number of contact surfaces between wheel and pipe
F_t	Tractive force (N)
r_w	Wheel radius (m)
k_1	Stiffness of gripping spring (N/m)
S_1	Deflection of gripping spring at rest position i.e., mode-II (m)
S_2	Deflection of gripping spring during mode-I (m)
μ	Coefficient of friction between rubber wheel and inner surface of acrylic pipe
T_i	Torque developed at *i*th wheel i= 1,2,3. (N/m)
Fs_1	Normal gripping spring force at rest position i.e. mode-II (N)
Fs_2	Normal gripping spring force during mode-I (N)
Fr_1	Friction force at each wheel at rest position i.e., mode-II (N)
Fr_2	Friction force developed at each wheel during mode-I (N)
Fr_3	Friction force between cam and follower (N)
T_m	Motor torque (N/m)
T_c	Torque required to rotate the cam (N/m)
r	Radius of cam base circle (m)
μ_c	Coefficient of friction between cam and follower
α	Angle between the line of action of W and the plane of gripping module plate (degree)
Z_1	Number of teeth on worm wheel
Z_2	Number of starts of worm
η	Machine efficiency

Author contribution statement

Gajanan Nikhade made a substantial contribution to the concept and design of Cam-operated In-Pipe Robot (CIPR). He has a major role in development of dynamic model, overall mechanism of (CIPR) and simulation in ADAMS.

Alok Jha has contributed in prototype design and experimentation of CIPR. He also contributed in ADAMS simulation.

Sharmik Admane has look after the electronics domain for the demonstration of CIPR.

Prajjawal Khandelwal plays a major role in preparation of CAD model and Drafting of the manuscript.

Yeshwant Sonkhaskar has contributed in the design and development of the three-lobed cam and drafting of the manuscript.

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