International Journal of Mechanical Engineering (IJME)
ISSN (P): 2319–2240; ISSN (E): 2319–2259
Vol. 10, Issue 2, Jul–Dec 2021; 51–66

International Academy of Science, Engineering and Technology
IASET
Connecting Researchers; Nurturing Innovations

A COMPREHENSIVE REVIEW ON PIPE INSPECTION ROBOTS

Aniket Nagesh Colvalkar, Sachin S. Pawar & Bhumeshwar K. Patle

Department of Mechanical Engineering, MIT ADT University, Pune, India

ABSTRACT

Pipe inspection is of great importance for assessing the integrity of the pipe in various pipeline industries. Pipe inspection eliminates human intervention from hazardous environments and accidents. There are multiple pipe inspection methods like X-ray, Magnetic acoustic testing, eddy current testing, and visual inspection, but pipe inspection using a robotic system is a promising one. A pipe inspection robot is usually fitted with a camera and other sensors that carry out a check. Due to geometrical changes of pipe-like joints, couplings, T sections, reducers, valves, while designing pipe inspection robots, various factors such as restricted manoeuvrability, complex designing, steering designing, adhesive forces during vertical motion have to be considered. This makes it necessary for proper designing and selection of mechanisms. Therefore, this paper provides a systematic review of various models that are available for pipe inspection. This paper will classify pipe inspection robots briefly into outer pipe inspection and inner pipe inspection robots.

KEYWORDS: *Pipe Assessment, Pipe Inspection Robot, In-Pipe Inspection, Outer Pipe Inspection, Camera*

Article History

Received:* *10 Nov 2021* | *Revised:* *13 Nov 2021* | *Accepted:* *24 Nov 2021

INTRODUCTION

Pipe inspection robot finds application in various industries such as petroleum, sewage treatment plant, water transporting pipelines, Gas industries, semiconductor, display fab, and so on [1]. Still, it is hard to find the right robot for various environments. Sometimes, Pipelines carry highly flammable materials. It is found that the integrity of these pipes is affected because of corrosion, cracks, deformation, and aging. Therefore, pipe inspection and maintenance are of immense importance to avoid any accidents. Most of the time, pipe inspection cannot be done from the surface, and the ones that can be done from the surface require highly skilled operators. Pipe inspection robots carry out various tasks such as detection of corrosion, deformation, build of scaling, deposits, etc. All the models are not capable of pipe inspection because some mechanisms are designed for external purposes, whereas some are designed for internal inspection [2].At present, there exist various types of pipe inspection robots. Different models are developed on outer pipe inspection [4-15] and inner pipe inspection robots [16-49]. Internal pipe inspections are the ones that move inside the pipe. This type provides internal visual inspection of the pipe, which cannot be done in a manual inspection. Since the robot moves inside the pipe, the internal status of the pipe provides more accurate observations. In contrast, external pipe inspection moves outside the pipe by gripping the outer surface of the pipe. This type of robot can inspect while the pipe is being used for transporting medium. This makes it more desirable because it can be carried out without affecting plant operation.

The Section follows will classify the models into internal pipe inspection and outer pipe inspection. These two types will be further classified in depth. In the end, the review will compare all the models. The paper will also look for research papers done in this field, and finally, it will look for limitations and research gaps.

CLASSIFICATION OF PIPE INSPECTION ROBOT

Pipe Inspection robots are classified as inner and outer pipe inspections. Pipe inspection robots are classified based on the gripping. External mechanisms include magnetic, gripper, and spring-assisted mechanisms, whereas inner type includes pipe inspection gauge (PIG), wheel type, Track type, snake type, inchworm type, walking type, and screw type. The following figure shows the detailed classification of inspection robots.

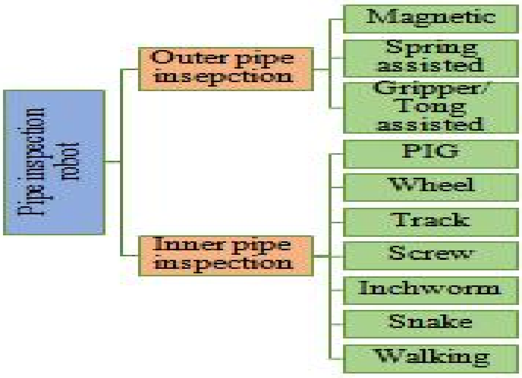

Figure 1: Classification of Pipe Inspection Robot.

Outer Pipe Inspection Robot

Outer pipe inspection robots are the ones that inspect the outer surface of the pipe by sticking on the outer surface. The main advantage of this type is that it can be operated even when the pipelines are transporting fluids, increasing the plant's productivity.

Magnetic Assisted Outer Pipe Inspection Robot Mechanism

As the name suggests, a magnetic assisted robot uses magnetic forces to stick outside the pipe during the inspection. The only limitation of this type is that the inspecting surface has to be ferromagnetic. Magnetic robots can be used for internal pipe inspection, but they are mostly preferred for external pipe inspection. Electro-Magnetic Acoustic transducer is one such example developed by Sangdeok Park et al. [4]. It moves from the outside but detects internal defects such as pinholes and cracks. They produced two robotic systems for inspecting boiler tubes to see all reductions in pipe walls above 1mm. Toshihiro Yukawa et al. [5] described a magnetic wheel used for inspecting pipelines made up of ferromagnetic material. They examined the mechanism of the robot and derived kinematics and adhesion conditions based on horizontal piping. They also studied the behaviour of magnetic adhesion force by using a magnetic wheel without a rubber and by using rubber coating. Vladimir Kindl et al. [6] dealt with redesigning the wheel and targeted to increase attraction force and reduce the overall mass of the wheel. They used finite element analysis and a nonlinear finite element approach for designing. Myounggyu Noh et al. [7] derived analytical force by calculating the reluctance force between mating surfaces. Finally, finite element analysis and test rig showed validation of the model. Minghui Wu et al. [8] focussed on adhesion force and mechanism for passing over an obstacle for wheel robot. The mechanism was provided to lift the body of the robot to avoid obstacles by varying adhesive forces. Zhongcheng Gui et al. [9] developed a robot for welding with colossal load carrying capacity and high adsorption reliability. Mahmoud Tavakoli et al. [10] showed an inchworm mechanism having two switchable magnets for adhesion. Peidró, A. et al. [13] presented designing, and implementation of magnetic grippers for exploring ferromagnetic structures using two designing approaches Zero-point moment and static friction analysis. At the time of the study, two failure modes were also studied: detaching and slippage. Andrew Garcia et al. [14] researched switchable magnets to investigate power efficiency. Naoto Imago et al. [15] fabricated Hermits crabs model having spokeless wheels made up of magnets.

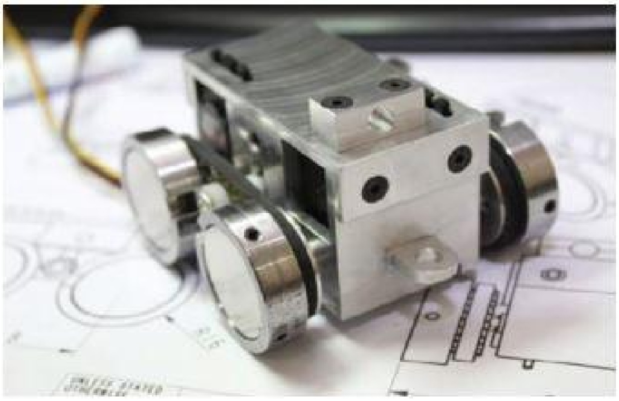

Figure 2: Magnetic Assisted Pipe Inspection Model [8]

Spring-Assisted Outer Pipe Inspection Mechanism

Spring is the most critical part of spring-assisted models. Spring provides the necessary gripping force for the structure. Therefore, the proper design of spring is essential. If the spring chosen has high strength, it will provide more gripping force, and if spring strength is low gripping force will be less. More gripping force may lead to sticking the model in one place, and its movements might be constricted. If force is not enough, the model will slip. Xu Fengyu et al. [16] designed a model to check for internal steel cracks and cylindrical cables and poles defects. The main objective was to create obstacle avoidance and climbing principles and analyze the dynamic characteristics of the model. Ram Sudhir et al. [17] developed a pole climbing model using a spring mechanism to climb up and down on the poles. Toshio Fukuda et al. [18] developed a model for a 90mm diameter pipe with arms with hook and tensioner by using spring arrangement. Tariq P. Sattar et al. [19] developed a pole climbing model to inspect wind turbine blades using a spring mechanism.

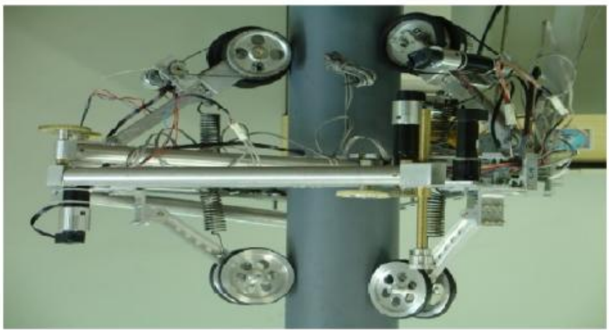

Figure 3: Spring-Assisted Pipe Inspection Model [2]

Gripper Assisted Outer Pipe Inspection Mechanism

The gripper is a simple mechanism that works precisely like a human hand. Both the links come together to gripe a pipe and to release the grip; links extend outward. The gripping mechanism could be controlled by hydraulic, pneumatic, suction, spring, or air vortex mechanisms. This is a simple mechanism compared to the above two mechanisms, but executing this mechanism requires special arrangement and additional space. F. Javier Garcia Rubiales et al. [20] developed a gripper mechanism for the unmanned aerial vehicle inspecting pipes. They ultimately developed a mechanism using additive techniques and tried out various tests to ensure grasping capacity. P. Ramon-Soria et al. [21] developed a gripping mechanism for aerial systems. Joshua Fishman et al. [22] worked on improving the grippers used for the aerial system. Earlier models required precise positioning and a larger contact area for successful gripping, but they have shown by replacing them with soft tendon actuators has provided firm gripping. Radhen Patel et al. [23] showed improvement in grasping ability using tactile sensors and proximity sensors. They studied various gripping phases such as approach, alignment, contact, lift, slip, disturbance, placement, and release. Hidemi Hosokai et al. [24] designed and implemented a lazy tongs mechanism to climb pipes of various diameters and detect reducer and diffuser. They studied an algorithm for motion control for the robot to pass over the reducer. Puneet Singh et al. [25] focused on designing and prototyping pipe climbing robots using external grippers. It had eight legs and a rotational joint for rotating along the longitudinal axis. Leg robot has better ability to avoid obstacles and navigational capacity to navigate over flanges, reducers, fixtures, etc.

Figure 4: Gripper Mechanism using Tongs [2].

INNER PIPE INSPECTION ROBOT

Inner pipe inspection robots inspect the pipe's inner surface by moving inside the pipe. This provides the internal status of the pipe, which is not possible by any other method. This process cannot be done when the pipes are underused, but few models like pipe inspection gauges can be done when the pipe is in use.

Pipe Inspection Gauge (PIG)

It is a type of robot that moves inside the pipeline using the kinetic energy of fluid flowing inside the pipe. This model does not have a self-driving mechanism, but it can carry several sensors onboard for inspection. These models have to be launched inside with the help of a PIG launcher, and after review, it has to be received by the same. The PIGs come in various sizes and diameters. Based on the diameter of suitable pipe, PIG is selected. Devesh Mishra et al. [26] Studied and designed a model for the inspection and maintenance of the pipeline. This model could measure diameter, inspect corrosion, deformation, detect leakage, and build-up of scale. They also studied kinematic analysis, pigging phenomenon, and hall effect. Oluwafemi Ayodeji Olugboji et al. [27] designed and developed an intelligent pipe inspection gauge to check the impulse experienced by the gauge when it travels inside the pipe. Impulse was detected by analyzing vibrations as it moved along the pipe. PIG could see its behaviour as well as simulated defects. They also showed the use of off-shelf sensing equipment is inexpensive. Giancarlo Bernasconi et al. [28] studied pipe inspection gauge tracking and positioning to achieve the best inspection possible. They have focused on three techniques to capture noise generated by PIG while in operation without extra onboard sensors. They have concentrated on pressure measurements at several positions. The first method gives location by analyzing the recorded acoustic signal on the opposite side of gauge travel. The second way is to count transient at known positions, and the third focuses on length measurement between PIG and Some resonating structures. Wasim M. F. Al-Masri et al. [29] proposed a navigation system for PIG using inertial navigation. They used two approaches, first an accurate dynamic model, in the second 3-dimensional reduced inertial sensor. On comparing both methods, they found out that the Second method produces more accurate data. For determining position, the length of the pipeline is measured, and encoded velocity constraints are utilized. Zheng Hu et al. [30] Proposed PIG with multidirectional travel capacity, i.e., it could travel in the direction of flow and opposite the flow. Xiaoxiao Zhu et al. [31] focused on frictional forces between contacting surfaces. The study also concentrated the effects produced by friction on the surface of PIG. John Faber Archila et al. [32] studied various parameters to be used while designing PIG pressure, the diameter of PIG, Fluid properties, external factors, and other important physical properties. Deng et al. [33] focused on the variation of speed by changing valve position on the PIG. The model was fitted with a pressure changing valve, which, when operated, could control the speed of PIG.

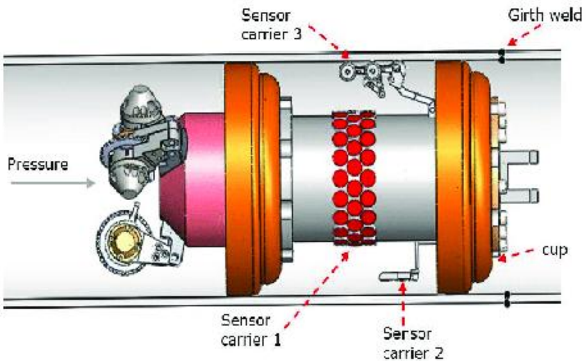

Figure 4: Pipe Inspection Gauge [26]

Wheel Type

The wheel type mechanism is most widely used because of its simplicity in construction, has less energy consumption, and is easy to manipulate. This type of model can relatively reach a higher speed as compared to any other model. There are various models such as the omnidirectional wheel model, single wheel (active wheel), Passive wheel, etc. This type requires only two mechanisms, one for driving and the other for gripping. Some of the wheel type models have been discussed below: “MAKRO” was the world’s first wheel type pipe inspection model. The main characteristic of this model was it could move in both directions. For micro pipe inspections less than 1 inch, “Toshiba” was developed that had good functionality. “THES-1” showed similar locomotion, but instead of wheels, it had rollers that could rotate spirally along the pipe axis without rotating its body. Apoorv Vikram Singh Bhadoriya et al. [34] designed a mini robot for narrow surfaces. Also, a solid work model was prepared of the same. Simulations were performed for vertical and horizontal pipe settings. Graphs of velocity vs. time and reaction force vs. time studied. Junghu Min et al. [35] Wheel-type model for pipe diameter 300-500mm was developed. They have designed a Proportional integral derivative controller to take into account linear and angular velocity. Muhammad Azri Abdul Wahed et al. [36] developed and experimented on a wheel-wall pressed type model that could vary between 150 mm to 230 mm. They also studied the behaviour of the model and its velocity when the angle of inclination was increased. H.R. Choi et al. [37] developed a wheel structure model like a snake with cables driving vehicles on front and back. They have used a special arrangement for steering called a double active universal joint that has eliminated rolling in the driving direction. Atul A. Gargade et al. [38] showed a comparative study of different in-pipe inspection robots and improved steering mechanisms. Edwin Dertien et al. [39] developed a model for omnidirectional wheels and for improving stability. A model with a V-shaped body frame was made to provide the necessary gripping for the pipe wall. This setup has provided very user-friendly control, which is the main benefit of the model.

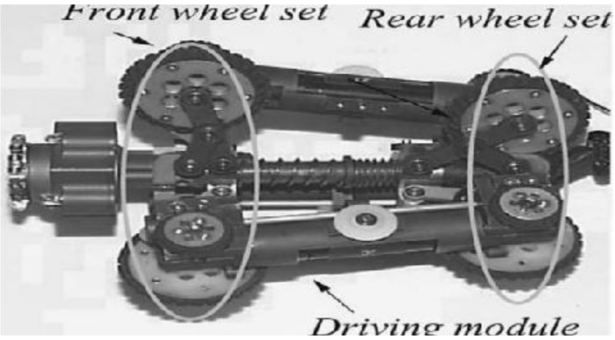

Figure 5: Wheel Type Inspection Model [38].

Track Type

Track type is an improved version of the wheel type robot. The advantage of track-type over any other model is that it provides extra frictional surface area, stability to the structure, and can carry more payload. The combination of wheel and track adds more stability on uneven surfaces, but the model is difficult to manipulate. Since more friction is involved therefore more force is required for motion. AURORA was the first track-type model prepared that had a single track. This model was made for pipeline inspection and maintenance purposes. Lei Zhang et al. [40] presented a model and carried out stability analysis for crawler type, which had radial adjustment mechanism. They have studied stability analysis in the straight pipe when climbing obstacles. While doing so, they have focussed on sliding and overturning conditions; also, stability analysis in the elbow was performed. Jong-Hoon Kim et al. [41] presented and designed a single module robot called “Famper” for up to 150mm diameter pipe inspection. They have shown that by using four caterpillar configurations, performance can be improved. Park, J. et al. [42] have developed “PAROYS-II” to overcome motion problems. It could effectively inspect pipes ranging from 400-700 mm. Atsushi Kakogawa et al. [43] analyzed the robot's speed during motion through straight pipe and bends and derived the speed of three diving modules while in curves. MohdZafri Baharuddin et al. [44] presented a mini model for boiler head inspection; it was tested and found to work as per the requirements. Zhang modified and showed the position and direction of a model. Young-Sik Kwon et al. [45] focused on a robot's omn motion planning algorithm for pipe diameter 80-100 mm. For gripping purpose 4 bar mechanisms and for steering differential drive is used. Zhang further modified a track-type robot and came up with an adaptable drive system. This model had four components: travel, differential, pre-adjusting, and supplementary supporting, coupled with a modular platform. “Neptune” was developed by Carnegie Mellon University, which could operate in a pipe of 1-meter diameter. It has cameras and ultrasonic sensors with remote control capacity. Ultrasonic Motion detectors play a massive role in obstacle avoidance.

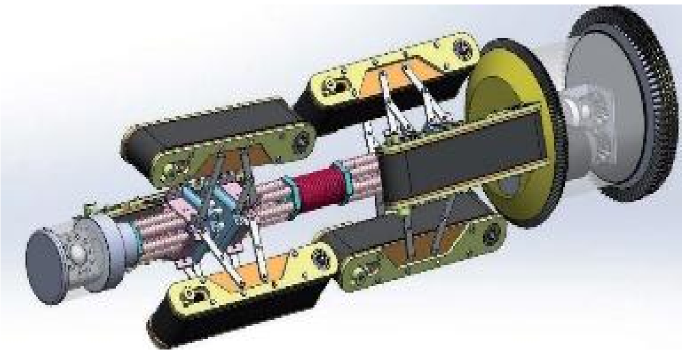

Figure 6: Track Type Inspection Model [41].

Screw Type

This type of robot requires only one degree of freedom and only one actuator. The robot's movement is because of the motor, tilted wheels, and a spring mounted on each arm. The angle of tilt determines the pitch of the robot's movement. The whole front body with arms rotates when the rotor rotates, and the wheels trace the pipe's inner surface. The movement is exactly like a screw, therefore the name Screw mechanism. Liu Qingyou et al. [46] studied the forces of gripping and locomotion for light load mechanism. They have realized that the springs remain neutral for a light load, and energy consumed is least of all. Using a linear quadratic regulator approach, H. Tourajizadeh's et al. [47] developed a steerable Screw type mechanism. A special arrangement was provided to change the pitch so that the steering angle could be changed to avoid obstacles. Tao Ren [48] focussed on discussion and analysis of existing screw drive robots and mainly focussed on variable radius screw drive mechanism based on planetary gear mechanism operated by a single motor. In the end, new and existing mechanisms were compared, and it concluded that the new model provided more traction force when models of same size and motor output were compared. Taiki Nishimura [49] focussed on improving the existing models by utilizing a pathway selection mechanism. Three parts require more attention: the screw driving unit, steering unit, and rotator unit. They have also worked on improving rear units; limitations due to improvements have been discussed thoroughly. Atsushi Kakogawa et al. [50] have carried out motion analysis and experiment analysis on screw-type robots. They have focussed on helical driving motion and performed experiments to find characteristic of it. Yin Zhang et al. [51] compared various screw drives in pipe robots in point of design, motion, driving mechanism, behaviour, parameters it inspects. Different models such as simple screw drive in-pipe robot, active screw drive robot, differential drive in-pipe robot, variable pitch, inchworm screw drive robot, and active screw drive in-pipe robot based on differential gear are studied. Ankit Nayak et al. [52] focussed on issues faced while designing in pipe inspection robot and proposed a model based on screw wall pressed adaptive mechanism. It could be easily manipulated through elbows, joints, and reducers, etc. They also through various trials and experiments showed that velocity attained by actual model matches with the mathematical model.

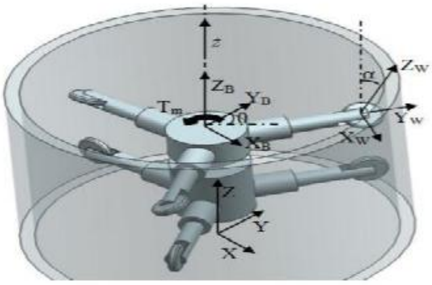

Figure 7: Screw Type Inspection Model [52]

Walking Type

This type uses legs or limbs that are pushed against the wall to support body and motion. This type of robot has a wide range of motions because of its high degrees of movement. They have complex mechanisms. Therefore it requires a more significant number of actuators. Siemens AG developed the first spider-like in pipe inspection robot. Sergei Savin et al. [53] studied state observer design for walking in pipe robots because of noise and limited data provided by the sensors. The study focused on the Riccati equation for improving the results. The simulation model showed that the use of state improves data capturing. Anna Ariga et al. [54] focused on fabricating a narrow robot between two walls, a novel wall-climbing robot that can move in vertical space. The pantograph and driving module is responsible for movement and stability. Xiaojie Tian et al. [55] studied and designed a combination robot for removing oil plugs well and prepared a mathematical model using FEM. The adaptive guiding mechanism, the supporting mechanism, and the electric guiding rod were collectively adapted to construct a micro-step walking mechanism. Werner Neubauer et al. [56] worked on a model that worked as a spider to climb vertical surfaces. Since this model had legs and walked like a spider, it could step over the obstacles and function smoothly even on rough surfaces. A reflective and reactive approach was used for controlling the motion of the robot. Andreas Zagler et al. [57] fabricated a model called "MORITZ." Moritz had two bending and revolving joints. R. Aracil et al. [58] proposed the Gough-Stewart platform as a climbing robot. They have proposed several mechanical designs; they have also carried out a dynamical analysis of these designs and prepared a prototype model for climbing palm trunks.

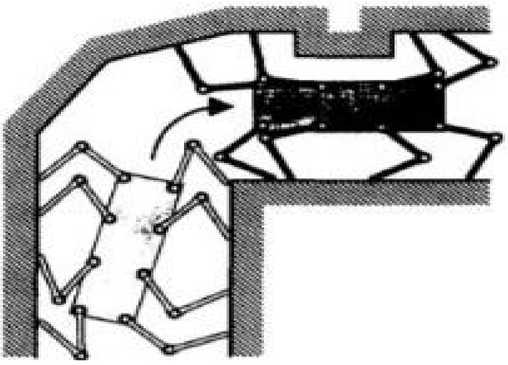

Figure 8: Walking Type Inspection Model [2]

Snake Type

Unlike other mechanisms like a wheel, track, or walking type, which uses wheels or legs for the motion. Snake type uses its body for propulsion. Most of the robots already have identical modules, and a propulsive mechanism is achieved by driving joints. The snake robot is biologically inspired and follows like an inchworm. The snake follows a travelling wave-like motion, and because of that, it has limited purposes. Thavida Maneewarn et al. [59] studied parameters that contribute to crawling and the effect of crawling motion. They have also fabricated a mini size 12 joints model and studied over five different motion shapes by varying inclination angles. They also concluded that a nonslip contact point is necessary for an effective motion of the robot in a vertical pipe. Shuichi Wakimoto et al. [60] developed a microrobot depicting snake mechanism and showed various characteristics of the snaking drive. They have also carried out experiments shoeing image stabilization and steering in branches using the micro model. Suzumori [61] proposed a snake drive mechanism and studied potential and fundamental characteristics with experimental data. They have also worked on deriving fundamental formulas, characteristics, and control algorithms. They have also focussed on deriving the additional formulas and characteristics for the front portion because it is an essential part of the steering component. Akina Kuwada et al. [62] fabricated a robot using a sinusoidal wave drive. They have also worked on intelligent actuators to reduce the wiring, improve performance, and provide high electrical noise tolerance. A. Brunete et al. [63] described kinematics close control loop for obstacle detection and avoidance in servomotor-controlled snake robot. They have also characterized and described modules including kinematics, control loops, and torque calculations. K. L. Paap et al. [64] built a snake robot to inspect pipelines that could be controlled remotely, and when the operator loses control, the robot could function autonomously. Florian Enner et al. [65] estimated the motion of the snake robot using the idea of the snake robot's joint angles. This model was designed such that by estimating motion traversing inside and outside diameter of pipe could be accurately found out. Anojan Selvarajan et al. [66] designed and worked on making the robot's motion smooth and noiseless by using many brackets. They have designed the brackets on fusion 360 and 3D printed the parts using PLA material. Yoshiaki Bando et al. [67] focussed on the localization of snake robots based on sound and inertial measuring unit. Localization using GPS and other options is not used because it may get damaged due to sudden uncontrolled movements, but in place of that microphone is placed on the robot, and the speaker is placed at the entrance of the robot, and the time of flight is calculated.

Figure 9: Snake Type Inspection Model [65]

Inchworm Type

Inchworm type is a biologically inspired robot that imitates like an inchworm. They have a high degree of freedom, require high number of actuators, are flexible, and have well-controlled motion. They have complex body designs, and because of that, they are mostly not preferred. Zheng Hu et al. [68] presented a self-driven model that uses bristles movements for the motion. They have conducted an experimental motion analysis for upstream and downstream movements. Another research by Zhelong Wang et al. [69] uses a similar bristle mechanism moved by piston and cylinder. The cylinder extends and retracts; this motion is transferred to the bristle motion, which looks like a caterpillar. Woongsun Jeon et al. [70] fabricated a model called extensor using an inchworm mechanism. He focussed on steering and navigation mechanisms, especially for T- section motion. It had two parts, upper and lower clamper, extended and retracted by piston and cylinder arrangement. Houxiang Zhang et al. [71] researched open and closed kinematic chain models based on crawling motion. He studied caterpillar and inchworm models. Keith Kotay et al. [72] fabricated a model moving in 3 dimensional using electromagnetic feet that stick to the walls. Tomonari Yamamoto et al. [73] developed a bidirectional inchworm mechanism by duplex chambered structure. They also studied locomotion techniques with mathematical formulations and analysis from an operational pressure point of view.

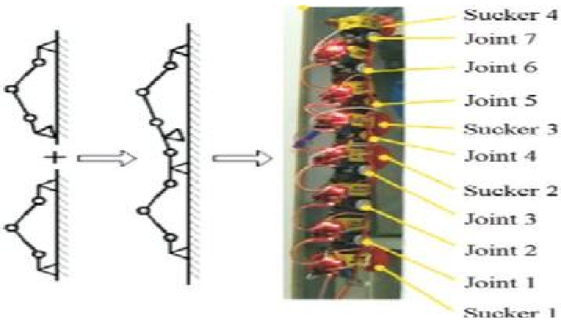

Figure 10: Inchworm Type Inspection Model [72].

CONCLUSIONS

Pipe inspection robots are classified as Internal pipe inspection and External pipe inspection. The study shows the following results:

- Classification of models provides better scope for the operator to select mechanisms based on his requirements and applications
- It was seen that the wheel type model was mainly preferred because of simplicity, and a smaller number of actuators are used.
- It is also seen that the inchworm mechanism has a smaller number of papers published to date.
- It is also seen that in some areas where locomotion is challenging to achieve, hybrid models provide better results.
- Inchworm and snake models, focus has been on locomotion of the model and less attention has been given to developing robust controllers.
- The screw mechanism is the most effective in locomotion, frictional force, steering ability, and a smaller number of actuators and kinematic pairs.
- There is enormous scope in developing a model that will provide better steering ability in T-sections and branches.

FUTURE SCOPE

The previous mechanisms developed have considerable limitations when moving inside T- sections, and branches. There is enormous scope in working towards improving the mechanisms that could easily overcome this limitation. Also, most of the mechanisms need wireless connections so that robots can move more distances with ease. By using machine learning and the Internet of Things, it is possible to add more functionality to the robots such as automatic fault detection, obstacle detection, and improvement in control.

REFERENCES

1. *Chao-Yung Yeh, Chen-Ya Chen, Jia-Yang Juang, "Soft Hopping and Crawling Robot for In-pipe Travelling," Extreme Mechanics Letters, Doi: https://doi.org/10.1016/j.eml.2020.100854.*
2. *P. Chattopadhyay, S. Ghoshal, A. Majumder and H. Dikshit, "Locomotion Methods of Pipe Climbing robots: A Review," Journal of Engineering Science and Technology Review 11 (4) (2018) 154 – 165.*
3. *Zheng L., Yehuda K., "State of the art review of inspection technologies for condition assessment of water pipes," Measurement 46 (2013) 1–15.*
4. *Sangdeok Park, Hee Don Jeong, and Zhong So0 Lim, "Development of Mobile Robot Systems for Automatic Diagnosis of Boiler Tubes in Fossil Power Plants and Large Size Pipelines," Intl. Conference on Intelligent Robots and Systems EPFL, Lausanne, Switzerland, October 2002.*
5. *Toshihiro Yukawa*, Masayuki Suzuki, Yuichi Satoh, Hideharu Okano, "Design of Magnetic Wheels in Pipe Inspection Robot", 2006 IEEE International Conference on Systems, Man, and Cybernetics October 8-11, 2006,*

6. *Vladimir Kindl, Karel Hruska, Roman Pechanek, Bohumil Skala "Redesign of an Undercarriage Wheel for a Self-Acting Robot", IEEE TRANSACTIONS ON MAGNETICS, VOL. 52, NO. 2, FEBRUARY 2016.*

7. *Myounggyu Noh, Eunsang Kwon, So Hee Park, Young-Woo Park, "Modeling of Attractive Force by Magnetic Wheel Used for Mobile Robot", actuators, August 2020, Doi: http://dx.doi.org/10.3390/act9030067.*

8. *Md Raziq Asyraf Md Zin, Khairul Salleh Mohamed Sahari, Juniza Md Saad, Adzly Anuar, Abd Talip Zulkarnain, "Development of a Low Cost Small Sized In-Pipe Robot", International Symposium on Robotics and Intelligent Sensors, doi: 10.1016/j.proeng.2012.07.337*

9. *Zhongcheng Gui, Yongjun Deng, Zhongxi Sheng, Tangjie Xiao, Yonglong Li, Fan Zhang, Na Dong, Jiandong Wu, "Design and Experimental Verification Of An Intelligent Wall-Climbing Welding Robot System", Industrial robots 41(6),117-124, Doi: http://dx.doi.org/10.1142/9789814623353_0014.*

10. *Jose Carlos Rom, Mahmoud Tavakoli, Carlos Viegas, Pedro Neto, Anibal T. de Almeida, "Inchworm Climber: A light-weight biped climbing robot with a switchable magnet adhesion unit", International Conference on Intelligent Robots and Systems, doi:10.1109/iros.2015.7353839*

11. *Toshio Fukuda, Hidemi Hosokaiy, Masashi Otsuka, "Autonomous pipeline inspection and maintenance robot with Inch worm mobile mechanism," The Science Univ. of Tokyo, Dept. of Mech 1-3 Kagura-zaka, Shinjuku-ku, Tokyo 162, Japan.*

12. *Kosuke Nagaya, Tomohiko Yoshino, Makoto Katayama, Iwanori Murakami, and Yoshinori and Yoshinori Ando, "Wireless Piping Inspection Vehicle Using Magnetic Adsorption Force," IEEE/ASME Transactions on Mechatronics, VOL. 17, NO. 3, (2012) 472 – 479.*

13. *Adrian Peidro, Mahmoud Tavakoli, Jose María Marína, Oscar Reinosoa, "Design of compact switchable magnetic grippers for the HyReCRo structure-climbing robot", structure-climbing robot. Mechatronics, 59, 199–212. doi:10.1016/j.mechatronics.2019.04.007.*

14. *Andrew Garcia*, *Mehrube Mehrubeoglu, "Switchable magnets as a power efficient alternative for electromagnets in a mobile robotic system", Green technologies conference 2020, Doi: https://doi.org/10.1109/GreenTech46478.2020.9289820.*

15. *Naoto Imajo, Yogo Takada, Mikiji Kashinoki, "Development and Evaluation of Compact Robot Imitating a Hermit Crab for Inspecting the Outer Surface of Pipes," Hindawi Publishing Corporation Journal of Robotics Volume 2015, Article ID 312780, 7 pages.*

16. *Fengyu, X., Jinlong, H., Bei, W., "The obstacle-climbing capability of a pole-climbing robot", Chinese Control Conference (CCC) (2015), doi:10.1109/chicc.2015.7260557.*

17. *Ram Sudhir, Pratik Kadam, Vishal Ubale, Vishal Shinde, Prof. Manjunath Kerakalamatti, "Design and Development of Pipe Climbing Robot," International journal of Engineering, Technology, management and Research, Vol 4, Issue 3, (2017), 414-419.*

18. *Toshio Fukuda, Hidemi Hosokaiy, Masashi Otsuka, "Autonomous pipeline inspection and maintenance robot with Inch worm mobile mechanism," The Science Univ. of Tokyo, Dept. of Mech 1-3 Kagura-zaka, Shinjuku-ku, Tokyo 162, Japan.*

19. *Mohd Zamzuri Ab Rashid, Mohd Fitri Mohd Yakub, Sheikh Ahmad Zaki bin Shaikh Salim, Normaisharah Mamata, Sharifah Munawwarah Syed Mohd Putra a, Shairatul Akma Roslan "Modeling of the in-pipe inspection robot: A comprehensive review", Ocean Engineering 203 (2020) 107206*

20. *F. Javier Garcia Rubiales, Pablo Ramon Soria, Begona C. Arrue, Anibal Ollero, "Soft-Tentacle Gripper for Pipe Crawling to Inspect Industrial Facilities Using UAVs",. Sensors 2021, 21, 4142. https://doi.org/10.3390/s21124142.*

21. *P. Ramon-Soria, A.E. Gomez-Tamm, F.J. Garcia-Rubiales, B.C. Arrue, A. Ollero1, "Autonomous landing on pipes using soft gripper for inspection and maintenance in outdoor environments", International Conference on Intelligent Robots and Systems (IROS) November 4-8, 2019, DOI:10.1109/IROS40897.2019.8967850.*

22. *Joshua Fishman, Samuel Ubellacker, Nathan Hughes, Luca Carlone, "Dynamic Grasping with a "Soft" Drone: From Theory to Practice", IROS 2021.*

23. *Radhen Patel, Jorge Canardo Alastuey, Nikolaus Correll, "Improving Grasp Performance Using In-Hand Proximity and Dynamic Tactile Sensing", International symposium on Experimental Robotics, DOI: 10.1007/978-3-319-50115-4_17.*

24. *Hidemi Hosokai, Fumio Hara, Yasuyuki Uchida, Yasunori Abe, Koetsu Tanaka, Yoshio Tanaka, "Mechanism and Control of Mobile Pipeline Maintenance Robot with Lazy Tongs Mechanism", International Conference on Robotics and Automation.*

25. *Devesh Mishra, Dr. Krishna Kant Agrawal, Ali Abbas, Dr. Rekha Srivastava, Dr. R. S. Yadav, "PIG [Pipe Inspection Gauge]: An Artificial Dustman for Cross Country Pipelines", International Conference on Pervasive Computing Advances and Applications, Procedia Computer Science 152 (2019) 333–340.*

26. *Oluwafemi Ayodeji Olugboji, Adinoyi Abdulmajeed Sadiq, Oluwafemi Olorunsaiye, David Omeiza Peters, Babatunde Ayobami Ajayi, "Development of A Smart Pipe Inspection Gauge for Detection of Pipeline Defects", International Mechanical Engineering Congress and Exposition, Volume 4B: Dynamics, Vibration, and Control. doi: 10.1115/imece2015-53064.*

27. *Giancarlo Bernasconi, Giuseppe Giunta, "Acoustic detection and tracking of a pipeline inspection gauge", Journal of Petroleum Science and Engineering,doi:10.1016/j.petrol, 194 (2020) 107549.*

28. *Al-Masri, W. M. F., Abdel-Hafez, M. F, Jaradat, M. A., "Inertial Navigation System of Pipeline Inspection Gauge", IEEE Transactions on Control Systems Technology, 1–8. doi:10.1109/tcst.2018.2879628.*

29. *Zheng Hu, Ernest Appleton, "Dynamic Characteristics of a Novel Self-Drive Pipeline Pig," IEEE Transactions on Robotics, Vol. 21, No. 5, October 2005.*

30. *Yun Du, Quan-min Zhu, Sabir Ghauri, Jian-hua Zhai, Hui-ran Jia, and Hassan Nouri, "Progresses in Study of Pipeline Robot," Proceedings of 2012 International Conference on Modelling, Identification and Control, Wuhan, China, June 24-26, 2012.*

31. *Xiaoxiao Zhu, Shimin Zhang, Xiaolong Li, Deguo Wang, Da Yu, "Numerical simulation of contact force on bi-directional pig in gas pipeline: At the early stage of pigging," Journal of Natural Gas Science and Engineering, 23 (2015) 127-138.*

32. *John Faber Archila, Marcelo Becker, "Study of Robots to Pipelines, Mathematical Models and Simulation," IEEE Latin American Robotics Symposium and Competition, 27 Oct. 2013.*

33. *Apoorv Vikram Singh Bhadoriyaa, Vijay Kumar Guptab, and Sujoy Mukherjee, "Development of In-pipe Inspection Robot", Materials Today: Proceedings 5 (2018) 20769–20776.*

34. *Junghu Min, Yuhanes Dedy Setiawan, Pandu Sandi Pratama, Sang Bong Kim, "Development and Controller Design of Wheeled Type Pipe Inspection Robot", International Conference on Advances in Computing, Communications and Informatics (ICACCI), 2014.*

35. *Muhammad Azri Abdul Wahed, Mohd Rizal Arshad, "Wall-press Type Pipe Inspection Robot", International Conference on Automatic Control and Intelligent Systems (I2CACIS). doi:10.1109/i2cacis.2017.8239055.*

36. *H.R. Choi, S.M. Ryew, "in Robotic system with active steering capability for internal inspection of urban gas pipelines", Mechatronics 12 (2002) 713–736.*

37. *Atul A. Gargade1, Dr. Shantipal S. Ohol, "Development of In-pipe Inspection Robot", Journal of Mechanical and Civil Engineering, Volume 13, Issue 4 Ver. VII (2016), PP 64-72. DOI: 10.9790/1684-1304076472.*

38. *Edwin Dertien, Mohammad Mozaffari Foumashi, Kees Pulles, Stefano Stramigioli, "Design of a robot for in-pipe inspection using omnidirectional wheels and active stabilisation," IEEE International Conference on Robotics and Automation, May (2014).*

39. *Lei Zhang and Xiao Wang, "Stable Motion Analysis and Verification of a Radial Adjustable Pipeline Robot", International Conference on Robotics and Biomimetics Qingdao, 3-7, (2016).*

40. *Kim, J. H., Sharma, G. and Iyengar, S. S., "FAMPER: A Fully Autonomous Mobile Robot for Pipeline Exploration," Proc. of the 2010 IEEE International Conference on Industrial Technology (ICIT), pp. 517-523, 2010*

41. *Park, J., Hyun, D., Cho, W. H., Kim, T. H. and Yang, H. S., "Normal-Force Control for an In-Pipe Robot According to the Inclination of Pipelines," IEEE Transactions on Industrial Electronics, Vol. 58, No. 12, pp. 5304-5310, 2011.*

42. *Atsushi Kakogawa, Shugen Ma, "Speed Analysis for Three Driving Modules of an In-pipe Inspection Robots for Passing through Bent Pipes", IEEE International Conference on Robotics and Biomimetics (ROBIO 2014). doi:10.1109/robio.2014.7090585.*

43. *Mohd Zafri Baharuddin, Juniza Md Saad, Adzly Anuar, Iszmir Nazmi Ismail, Nur Maisurah Hassan Basri, Nur Shahida Roslin, Syed Sulaiman Kaja Mohideen, Muhammad Fairuz Abdul Jalal, Khairul Salleh Mohamed Sahari, "Robot for Boiler Header Inspection "LS-01"", Procedia Engineering, 41, 1483–1489. doi:10.1016/j.proeng.2012.07.339.*
44. *Kwon, Y.-S., Yi, B.-J. (2012) "Design and Motion Planning of a Two-Module Collaborative Indoor Pipeline Inspection Robot", IEEE Transactions on Robotics, 28(3), 681–696. doi:10.1109/tro.2012.2183049.*
45. *Liu Qingyou, Ren Tao, Yonghua Chen, "Characteristic analysis of a novel in-pipe driving robot," Mechatronics 23 (2013) 419–428.*
46. *H. Tourajizadeh, M. Rezaei, A. H. Sedigh, "Optimal Control of Screw In-pipe Inspection Robot with Controllable Pitch Rate", J Intell Robot Syst, J Intell Robot Systhttps://doi.org/10.1007/s10846-017-0658-7.*
47. *Tao Ren, Qingyou Liu, Yujia Li, Yonghua Chen, "Design, analysis and innovation in variable radius active screw in-pipe drive mechanisms," International Journal of Advanced Robotic Systems, May-June (2017) 1–9.*
48. *Taiki Nishimura, Atsushi Kakogawa, Shugen Ma, "Improvement of a Screw Drive In-Pipe Robot with Pathway Selection Mechanism to Pass Through T-Branches," Journal of Robotics and Mechatronics, Vol.25 No.2, 2013.*
49. *Atsushi Kakogawa, Shugen Ma, "Mobility of an In-pipe Robot with Screw Drive Mechanism inside Curved Pipes", International Conference on Robotics and Biomimetics December 14-18, (2010).*
50. *Tao Ren 1, Yin Zhang, Yujia Li, Yonghua Chen, Qingyou Liu, "Driving Mechanisms, Motion, and Mechanics of Screw Drive In-Pipe Robots: A Review", Appl. Sci. 2019, 9, 2514; doi:10.3390/app9122514.*
51. *Ankit Nayak, S. K. Pradhan, "Design of a New In-Pipe Inspection Robot", Procedia Engineering 97 ((2014) 2081 – 2091.*
52. *Savin, S., Jatsun, S., Vorochaeva, L. "State observer design for a walking in-pipe robot", MATEC Web of Conferences, 161, 03012. doi:10.1051/matecconf/20181610301.*
53. *Ariga, A., Kobayashi, T., Yamaguchi, T., Hashimoto, "Wall climbing robot in narrow space with pantograph-type structure", 2010 IEEE International Conference on Robotics and Biomimetics. doi:10.1109/robio.2010.5723553.*
54. *Xiaojie Tian, "Finite Element Analysis Based Design of Mobile Robot for Removing Plug Oil Well," Journal of Computers, VOL. 8, NO. 6, JUNE 2013.*
55. *Werner Neubauer, "A Spider-Like Robot that Climbs Vertically in Ducts or Pipes," International conference on Intelligent robots and systems, 06 August 2002.*
56. *Andreas Zagler, Friedrich Pfeiffer, ""MORITZ" a Pipe Crawler for Tube Junctions," International Conference on Robotics and Automation, 19 Sept. 2003, 1050-4729.*
57. *R. Aracil a, R. Saltarén a, O. Reinoso, "Parallel robots for autonomous climbing along tubular structures", Robotics and Autonomous Systems 42 (2003) 125–134, doi: 10.1016/s0921-8890(02)00360-3.*
58. *Maneewarn, T., Maneechai, B., "Design of pipe crawling gaits for a snake robot", 2008 IEEE International Conference on Robotics and Biomimetics. doi:10.1109/robio.2009.4912970.*

59. *Wakimoto, S., Nakajima, J., Takata, M., Kanda, T., & Suzumori, K., "A micro snake-like robot for small pipe inspection", Proceedings of 2003 International Symposium on Micromechatronics and Human Science (IEEE Cat. No.03TH8717). doi:10.1109/mhs.2003.1249959.*

60. *Suzumori, K., Wakimoto, S., & Takata, M., "A miniature inspection robot negotiating pipes of widely varying diameter", 2003 IEEE International Conference on Robotics and Automation (Cat. No.03CH37422). doi:10.1109/robot.2003.1242006.*

61. *Kuwada, A., Tsujino, K., Suzumori, K., & Kanda, T. (2006), "Intelligent Actuators Realising Snake-like Small Robot for Pipe Inspection", 2006 IEEE International Symposium on MicroNanoMechanical and Human Science. doi:10.1109/mhs.2006.320333.*

62. *Brunete, A., Gambao, E., Torres, J. E., & Hernando, M., "A 2 DoF Servomotor-based Module for Pipe Inspection Modular Micro-robots", 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems. doi:10.1109/iros.2006.281898.*

63. *Paap, K. L., Christaller, T., & Kirchner, F., "A robot snake to inspect broken buildings. Proceedings", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000) (Cat. No.00CH37113). doi:10.1109/iros.2000.895277.*

64. *Enner, F., Rollinson, D., & Choset, H., "Motion estimation of snake robots in straight pipes", IEEE International Conference on Robotics and Automation. doi:10.1109/icra.2013.6631316.*

65. *Selvarajan, A., Kumar, A., Sethu, D., & bin Ramlan, M. A. (2019). Design and Development of a Snake-Robot for Pipeline Inspection. 2019 IEEE Student Conference on Research and Development (SCOReD). doi:10.1109/scored.2019.8896254.*

66. *Bando, Y., Suhara, H., Tanaka, M., Kamegawa, T., Itoyama, K., Yoshii, K, Okuno, H. G., "Sound-based online localisation for an in-pipe snake robot", IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR). doi:10.1109/ssrr.2016.7784300.*

67. *Zheng Hu, Ernest Appleton, "Dynamic Characteristics of a Novel Self-Drive Pipeline Pig", IEEE TRANSACTIONS ON ROBOTICS, VOL. 21, NO. 5, OCTOBER 2005.*

68. *Zhelong Wang, "A Bristle-Based Pipeline Robot for Ill-Constraint Pipes", IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 13, NO. 3, JUNE 2008.*

69. *Jeon, W., Park, J., Kim, I., Kang, Y.-K., & Yang, H. (2011). Development of high mobility in-pipe inspection robot. 2011 IEEE/SICE International Symposium on System Integration (SII). doi:10.1109/sii.2011.6147496.*

70. *Wang, W., Wang, K., & Zhang, H. (2009). Crawling gait realisation of the mini-modular climbing caterpillar robot. Progress in Natural Science, 19(12), 1821–1829. doi:10.1016/j.pnsc.2009.07.009.*

71. *Keith Kotay, Daniela Rus, "The Inchworm Robot: A Multi-Functional System," Autonomous Robots 8, 53–69 (2000).*

72. *Tomonari Yamamoto, Sayako Sakama, Akiya Kamimura, "Pneumatic Duplex-Chambered Inchworm Mechanism for Narrow Pipes Driven by Only Two Air Supply Lines", IEEE ROBOTICS AND AUTOMATION LETTERS, VOL. 5, NO. 4, OCTOBER 2020.*