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Robotic Inspection Monitoring System for Pipelines

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Abstract

The most popular method for transporting fluids and gases is through pipelines nowadays. Regular inspection is necessary for the pipelines to work correctly. Humans must not enter potentially dangerous environments to inspect these pipelines. As a result of this, pipeline robots came into existence. These pipe inspection robots help in pipeline inspection, protecting numerous people from harm since human beings cannot enter the pipes and inspect them in case there is any such or kind of damage that requires repair. Despite numerous improvements, pipeline robots still have several limitations. The introduction of this in pipe inspection robots helps to solve many problems, such as leakage of the gas or fluid pipelines, rustiness, and also if the pipe is broken from any part.

Keywords

Inspection robot, Leakage, Pipeline, Broken

1. Introduction

Pipelines are now the most widely used method of transport for gases and liquids (63-65). Therefore, ongoing pipeline monitoring is necessary to assure its safety and health [1]. The most widely utilized Non-Destructive Testing (NDT) inspection techniques are optical testing, radiographic testing, ultrasonic testing, and hydrostatic testing, among others [2]. However, because of recent advancements in robotic technology [66, 67], they are now the preferable choice. Robots are a superior choice because it is challenging for people to access a small pipeline [3]. In-Pipe Inspection Robots (IPIR) have undergone a great deal of improvement recently, and these advancements are categorized according to their various locomotion patterns. Fig. 1 shows examples of the Pipeline Inspection Gauge (PIG) [9, 10], screw [16, 17], inchworm [18–24], wall press [25–29], walking [30–34], caterpillar [35–39], and wheel type [40–41], [50–52], [42–49]. These popular forms of movement have drawbacks in addition to their benefits [53].

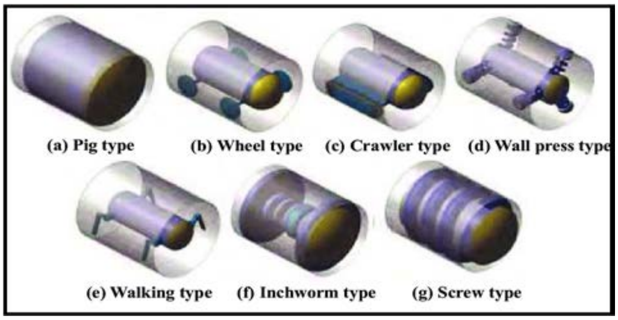

Figure 1 Different types of In-Pipe Inspection Robots

1.1. Robotic In-Pipe Inspection Types (IPIR)

The PIG type can be utilized for large distances [4]–[8] and moves inside pipelines using water pressure. The inside surface of the pipelines are not harmed by the screw-helical type's motion when it moves [11–15]. The inchworm may pass through pipelines because of its strong grasp despite its poor traction [18–22]. The wall press type steadily passes through the pipelines by using contact force [25–29]. The walking kind employs legs to move and has a complex mechanism, which causes reduced surface wear and slippage [30]–[34]. Caterpillars move inside pipelines using tracked wheels, and its system enables them to adjust to the circumstances there [35–39]. The wheel type is more mobile than the other varieties and can travel inside pipelines by simply rotating its wheels [40–44]. Due to the pipeline's curved and branching pipes, these robots must overcome numerous obstacles. It encounters motion singularity and erratic motion while doing this.

1.2. Motion Singularity

The "Motion Singularity" is the loss of contact between a robot and pipeline intersections such curved pipes, L-branch pipes, and T-branch pipes [54], [55]. Due to its powerful traction force and substantial contact area, the caterpillar robot offers more stability and is the most widely used IPIR. The pipeline is kept in contact with the inner surface no matter how the pipeline is turning by using tracked wheels [35-39] and [54-55]. If one of the wheels loses contact with the inner surface of the pipe, it is unable to pass through it, leading to motion singularity [54]. In Figure 2, a caterpillar robot that is travelling through T-branch pipes uses two modules in place of one to prevent motion singularity. Three caterpillar wheels are mounted on the first module at a 120° angle to one another, and the second module is infix at a 60° angle to the front module [54]. A pipeline exploration robot named "FAMPER" loses contact with the inner surface of the pipeline while turning at Y and T-branch pipes, which results in motion singularity. The caterpillar wheels were positioned at a 5-degree inclination with regard to the robot body rather than set straight to compensate for the loss of contact. "Motion singularity" is thereby avoided [55]. A two-wheel chain robot that avoids the motion singularity is shown in [56].

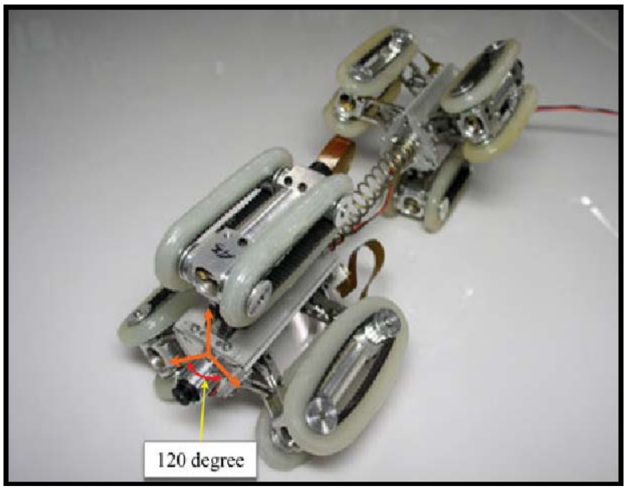

Figure 2 Two-Module Collaborative Indoor Pipeline Inspection Robot

1.3. Irregular Motion

According to published research, many conventional wheeled robots use wheels that are symmetrically positioned at a 120° angle to ensure even loading and improved stability while moving through pipelines. The wall press characteristic is how the wheeled robots acquire this stability [35], [54], [57-59]. According to [41, 42], the inclusion of six wheels corrects the uneven motion that occurs along the circumferential axis of the pipeline in forward motion caused by the three-wheel arrangement in wheeled IPIR. The wheeled robot has a three-wheel layout and moves inside the pipelines using two different types of wheels. One has single wheels, whereas the other has double wheels, as seen in Figure 3.

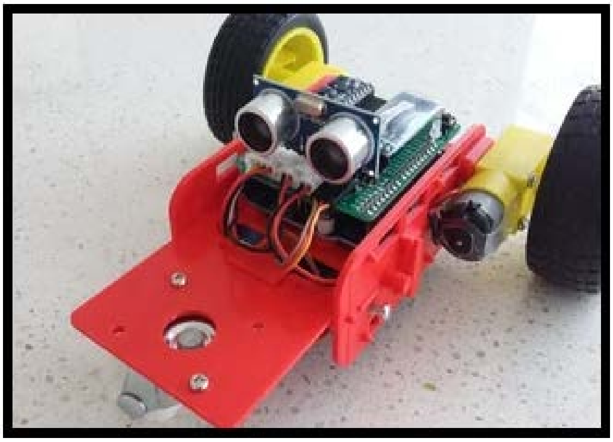

Figure 3 Three-wheel configuration robot

When moving forward, the robot's single three-wheel design tries to rotate in the pipeline's circumferential direction [60]. Only straight pipelines have been the subject of investigations about their motion. The orientation of the robot at the completing end is different from the starting end in circumstances [61] where it tries to roll over in order to maneuver through the curved pipeline. Additionally, steering inside branching pipes is challenging due to how the wheels are positioned. In order to avoid motion singularity and irregular motion while retaining the same orientation before and after entering the curved pipeline, this research focuses on constructing a wheeled IPIR with a single three-wheel arrangement [62].

1.4. Contribution

In order to address the issue of irregular motion and motion singularity occurring in pipelines, a wheeled type IPIR is proposed and developed in this research. The wheels on this robot are different from those on conventional robots in that they are not fixed at a 120-degree angle from one another. The location of the wheels guarantees that the robot's wheels are always in contact with the pipe surface and prevents the robot from rolling over when moving along a curved pipeline. It also aids the robot's navigation through branched pipes [62].

2. Resources and Techniques

Initially, we used the Solidworks program to design the robot. To ADAMS, the created model is exported. Using the limitations listed in the flowchart, motion analysis is performed for the robot. The findings are then discussed. Links, wheels, clamps, a central shaft, legs, a spring, a fixed joint, and a prismatic joint are all features of the proposed robot. Inside pipelines, the legs provide improved stability. The legs are supported by the small linkages. All of the parts are kept where they belong thanks to the clamps. The wheels are designed to increase mobility within pipelines. All of the modular parts are linked to the central shaft, which serves as the primary body. The prismatic joint, which is the moveable joint and the one that generates the force required for the wheels to make contact with the inner surface of the pipeline, moves while the fixed joint remains stationary. Spring-based devices that compress and expand in accordance with the inner circumference of the pipeline supply the necessary force for the prismatic junction. The internal pipeline diameter of the robot can range from 250 mm to 350 mm. It has three revolute joints and one prismatic joint. By compressing and stretching the legs, these joints provide the robot extra stability as it travels through the pipelines. It helps the robot deal with various pipeline scenarios, such curved or T-branch pipes. The actuator scale is ascertained using static analysis.

3. Discussion and Analysis

The ADAMS software does the motion analysis. The robot design is imported from Solidworks and the boundary conditions for the simulation are provided by the ADAMS software. Body-to-body contact, motor rpm, and spring stiffness are taken into account. Simulations are done for the proposed robot as well as the conditions when the wheels are offset by 120 degrees. In the scenario, the robot first travels inside a 350mm-diameter pipeline. After traveling 600 mm, the pipeline's inner diameter changes; it decreases by 10 mm, or 340 mm overall. The robot's capacity to adjust to pipelines of various diameters is tested by this shift in diameter. The robot then passes through a straight pipe once more before coming to a 90° curved elbow. It enters the straight pipe once more after leaving the curved pipe to exit the pipeline. This simulation scenario tests the robot's ability to move through pipes that are straight, curved, and of different diameters. The only difference between the simulations' parameters is the angle at which the wheels are mounted. Gravity, motor speed, solid body contact, and spring stiffness are the criteria the robot must meet in order to travel through the pipelines. The third wheel serves as a support wheel, making the three wheels at the bottom of the robot's front side functional. The robot has three inactive wheels at the back. The motor spins at 100 rpm, and the spring stiffness is 2.826 N/mm.

3.1. Robot with Wheels for Pipe Inspection

Traditional wheeled IPIRs have wheels that are 120 degrees apart from one another. The angle is calculated between the centers of each wheel and the central axis of the robot body. The homogeneous wheel mounting angle results in the motion singularity. The prismatic junction between the three legs allows them to compress uniformly as they pass through the pipeline. Motion singularity consequently develops inside curved pipelines. Wheel 1 rotates with a greater angular velocity than wheels 2 and 3, which remain stationary. The three wheels' angular velocity is constant as the inner diameter of the pipe shrinks. The robot then attempts to enter the curved pipeline, but wheel 3 loses contact, preventing the robot from doing so. It demonstrates that wheel 3's angular velocity, which should have been high when it traversed the concave region of the pipe, has remained constant in magnitude. The fact that it lost contact with the pipe wall is thus demonstrated. A maximum force of approximately 11.25 N is applied to wheels 1, 2, and 3 as the robot goes through a 350 mm pipeline. Wheels 1 and 2 encounter the most force when the pipeline diameter is increased to 340 mm, whilst wheel 3 experiences a decrease in forces. The forces pulling on the wheels then cease to exist. Wheel 3 experiences an increase in force when the robot enters the curved pipeline because the wheel loses touch with the concave portion of the inner pipeline surface. When the robot tries to travel through a curved pipe, it loses contact with one of the wheels and is unable to do so; however, the two wheels that are still in contact exert a force on the spring, which is why wheel 3 has a high spike after losing contact. The spring force causes the wheels to push the robot backward, which causes wheel 3 to hit the inside of the pipe and generate a huge force spike. Here, springs 1 and 2 refer to the springs in the front and back of the robot, respectively. When the robot passes through a pipeline with a 350 mm inner diameter, the force supplied by springs 1 and 2 ranges from 1.25 to 12.5 N. When the inner pipeline diameter reaches 340 mm, the force generated by springs 1 and 2 approaches 17.5 N. The robot cannot move through the curved pipeline because of motion singularity, which causes the force in spring 1 to decrease. Motion singularity causes the back half to exert a slight push at that precise moment because of the inertia of motion. As a result, the legs on the robot's back compress, producing a strong force of roughly 25 N at first before progressively reducing. It moves at an average linear velocity of 0.35 m/s while inside the 350 mm straight pipeline. The linear speed of the robot varies between

0.30 and 0.35 m/s when the inner diameter of the pipeline drops to 340 mm. The robot then tries to enter the curved pipeline but is unable to do so due to motion singularity, causing a sharp fall in linear velocity.

3.2. Wheeled IPIR design modification

The suggested wheeled design Inspection of the Pipe The wheels are asymmetrically and at various angles mounted by the robot. The arrangement of the wheels results in angles that are 120°, 104.88°, and 135.12° apart from one another. Calculations are made to determine the angle between the central axes of each wheel and the body of the robot.

In the curved pipeline, a robot With the exception of the wheel mounting angle, it uses the same mechanism as a conventional robot with wheels. The motion singularity in the curved pipeline is therefore avoided by the suggested design. The angular velocity of all three wheels remains constant as the robot moves through a straight pipeline with an inner diameter of 350 mm. When the inner pipeline diameter was reduced to 340 mm, small spikes in angular velocity were observed. After then, it moves via a straight pipeline with a constant angular velocity for the three wheels. The angular velocity of wheel 3 increases while that of wheels 1 and 2 decreases as the robot moves along the curved pipeline. Wheel 3 has a higher magnitude than the other two wheels because it travels through the concave portion, which causes its angular velocity to increase. This demonstrates that the robot's wheels are in contact with the ground as it travels through the bent conduit. After leaving the curved pipe, it enters a straight pipeline where the three wheels' angular velocities are held constant. As they go along the curved pipeline, there are increased forces on all three wheels. The forces ranging from 2.5 to 10 N are equally distributed among the three wheels. The springs utilized in the front and back of the robot are numbered 1 and 2, respectively. When going through a straight pipe with an inner diameter of 350 mm, spring 1 exerts a force of 11 N. When the inner diameter of the pipe is reduced to 340 mm, spring 1's force increases to 17.25 N. The robot travels through the curved pipe with a force of 15.65 N being applied by spring number one. It enters the straight pipe after leaving the curved one, providing the same spring 1 force of 17.25 N. Spring 2 follows the same pattern as it moves through the pipeline. The robot moves at a linear speed of 0.39 meters per second inside a straight pipeline with an inner diameter of 350 millimeters. It then has a linear velocity of 0.36 m/sec when the inner diameter is changed to 340 mm. The speed of the object falls off as it approaches the convex portion of the curved pipeline wheels 1 and 2. As the wheel moves through the concave portion of the curve pipe, its speed increases. It recovers to 0.36 m/s in speed as it re-enters the straight pipeline. Until it exits the pipeline, it keeps moving at this constant speed. The robot moves at an average speed of 0.33 m/s across both straight and curved pipes because its velocity cannot be determined directly because the three wheels have various magnitudes there. All three wheels are moving inside a straight pipeline with an inner diameter of 350 mm, and the angular velocity is constant for all three. Even after reducing the inner diameter to 340 mm, this remained the same. It departs from the straight pipeline and then merges with the curved pipeline. Wheels 1 and 2 are moving at an angle as they pass through the concave portion of the pipeline. Wheel 3 also experiences a decrease in angular velocity when it passes through the concave portion of the pipeline. Wheel 2's greater angular velocity suggests that it was in contact with the pipeline's inner surface and so prevented motion singularity. After leaving the curved tunnel, it proceeds into a straight pipeline, where all three wheels' angular velocities stay constant. The forces pulling on all three wheels of the robot rise as it travels through the curved pipeline. With forces ranging from 2.5 N to 12 N, the forces applied on all three wheels are roughly similar. While entering a 350 mm inner diameter pipeline, spring 1's 11 N force remains constant. As the pipeline's inner diameter decreases to 340 mm, the spring's first force rises to 17.25 N. The spring force then decreases to 15.5 N while passing through the curved pipeline, and when it re-enters the straight pipeline, it rises to 17.25 N. Spring 2 follows this same force trend as it travels through the pipeline. Robot travels at a speed of 0.39 meters per second as it passes a straight pipeline with an inner diameter of 350 millimeters. The robot moves at a speed of 0.36 meters per second when its inner diameter is reduced to 340 mm. Wheels 1 and 2 move more quickly through the bent pipeline as wheel 3 moves less quickly. Wheel 2 travels through the pipeline's concave portion, while Wheel 3 travels through the pipeline's convex portion, causing the increase and decrease. When the robot enters the straight pipeline, its speed drops to 0.36 meters per second. The robot moved at an average speed of 0.33 m/sec both inside the straight and curved pipelines.

4. Robots for Inspecting Pipelines

(1) Extreme security: Use the pipeline robot to enter the pipeline to efficiently discover the interior conditions of the pipeline or remove any concealed dangers.

Because of the high labor intensity and greater safety risks associated with manual labor, these jobs are not good for employees' health. The Easy Sight pipeline robot's intelligent operation may significantly enhance the operation's performance in terms of safety.

(2) Labor-saving: Small and lightweight, the pipe inspection robot can be controlled by one person. The controller can be put on the vehicle, which will save time and room.

(3) Increased effectiveness and caliber: The smart pipeline robot from Easy Sight can display real-time data such date and time, crawler inclination (pipeline slope), air pressure, crawling distance (meters of line), laser measurement results, and azimuth in addition to accurate positioning (optional). The function keys allow you to control the clock display of the lens angle of view as well as the display status of this information (positioning of pipeline defects).

(4) Great level of protection: There is no need to be concerned about the pipe camera's quality because it has a high level of protection, airtight protection, and the material is waterproof, anti-rust, and corrosion resistant..

(5) Receiving and releasing cables won't interfere with one another with a high-precision cable reel, and the length is configurable. The pipe inspection robot can inspect pipelines with diameters ranging from 100 mm to 2000 mm. It can raise productivity and save labor in addition to enhancing task precision. Additionally, it can maintain the pipeline in some locations where manual labor is not appropriate and quickly identify the internal sources of pipeline degradation [68].

5. Conclusion

In this work, we contrast the suggested wheeled type IPIR with the wheeled type IPIR that is currently in use. The three wheels are mounted on the current design at a 120° angle from one another. Both the suggested and conventional wheeled forms of IPIR are simulated. The ideal angles are 104.88°, 135.12°, and 120°. Results of velocity and force analyses for each wheel demonstrate how this design brings the wheels into contact with the pipelines. The created robot did not experience the unequal force experienced by the robot with a wheel mounting angle of 120° when traversing the curved pipeline. Also discussed are the effects of the in-pipe wheel robots.

References

[1] M. A. Adegboye, W. K. Fung, and A. Karnik, “Recent advances in pipeline

monitoring and oil leakage detection technologies: Principles and approaches," Sensors (Switzerland), vol. 19, no. 11, 2019, doi: 10.3390/s19112548.

[2] A. A. Carvalho, J. M. A. Rebello, M. P. V. Souza, L. V. S. Sagrilo, and S. D. Soares, "Reliability of non-destructive test techniques in the inspection of pipelines used in the oil industry," International Journal of Pressure Vessels and Piping, vol. 85, no. 11. 2008. doi: 10.1016/j.ijpvp.2008.05.001.

[3] A. Kakogawa and S. Ma, "Robotic Search and Rescue through In-Pipe Movement," in Unmanned Robotic Systems and Applications, 2020. doi: 10.5772/intechopen.88414.

[4] J. Zhou, T. Deng, J. Peng, G. Liang, X. Zhou, and J. Gong, "Experimental study on pressure pulses in long-distance gas pipeline during the pigging process," Sci. Prog., vol. 103, no. 1, 2020, doi: 10.1177/0036850419884452.

[5] H. Zhang, J. Dong, C. Cui, and S. Liu, "Stress and strain analysis of spherical sealing cups of fluid-driven pipeline robot in dented oil and gas pipeline," Eng. Fail. Anal., vol. 108, p. 104294, 2020, doi: 10.1016/j.engfailanal.2019.104294.

[6] C. Liu, Y. Wei, Y. Cao, S. Zhang, and Y. Sun, "Traveling ability of pipeline inspection gauge (PIG) in elbow under different friction coefficients by 3D FEM," J. Nat. Gas Sci. Eng., vol. 75, no. December 2019, p. 103134, 2020, doi: 10.1016/j.jngse.2019.103134.

[7] J. Jiang, H. Zhang, B. Ji, F. Yi, F. Yan, and X. Liu, "Numerical investigation on sealing performance of drainage pipeline inspection gauge crossing pipeline elbows," Energy Sci. Eng., vol. 9, no. 10, 2021, doi: 10.1002/ese3.955.

[8] J. Dong, S. Liu, H. Zhang, and H. Xiao, "Experiment and simulation of a controllable multi-airbag sealing disc of pipeline inspection gauges (PIGs)," Int. J. Press. Vessel. Pip., vol. 192, 2021, doi: 10.1016/j.ijpvp.2021.104422.

[9] Z. Chen, "Deformation and stress analysis of cup on pipeline inspection gauge based on reverse measurement," Energy Sci. Eng., no. January, pp. 2509–2526, 2022, doi: 10.1002/ese3.1241.

[10] H. Zhang, M. Q. Gao, B. Tang, C. Cui, and X. F. Xu, "Dynamic characteristics of the pipeline inspection gauge under girth weld excitation in submarine pipeline," Pet. Sci., vol. 19, no. 2, 2022, doi: 10.1016/j.petsci.2021.09.044.

[11] T. Ren, Y. Zhang, Y. Li, Y. Chen, and Q. Liu, "Driving mechanisms, motion, and mechanics of screw drive in-pipe robots: A review," Appl. Sci., vol. 9, no. 12, 2019, doi: 10.3390/app9122514.

[12] H. Tourajizadeh, V. Boomeri, M. Rezaei, and A. Sedigh, "Dynamic Optimization of a Steerable Screw In-pipe Inspection Robot Using HJB and Turbine Installation," Robotica, vol. 38, no. 11, 2020, doi: 10.1017/S0263574719001784.

[13] T. Li, K. Liu, H. Liu, X. Cui, B. Li, and Y. Wang, "Rapid design of a screw drive in-pipe robot based on parameterized simulation technology,"

Simulation, vol. 95, no. 7, 2019, doi: 10.1177/0037549718799881.

[14] H. Tourajizadeh, M. Rezaei, and A. H. Sedigh, "Optimal Control of Screw In-pipe Inspection Robot with Controllable Pitch Rate," J. Intell. Robot. Syst. Theory Appl., vol. 90, no. 3–4, 2018, doi: 10.1007/s10846-017-0658-7.

[15] P. Li, M. Tang, C. Lyu, M. Fang, X. Duan, and Y. Liu, "Design and analysis of a novel active screw-drive pipe robot," Adv. Mech. Eng., vol. 10, no. 10, 2018, doi: 10.1177/1687814018801384.

[16] Q. Tu, Q. Liu, T. Ren, and Y. Li, "Obstacle crossing and traction performance of active and passive screw pipeline robots," J. Mech. Sci. Technol., vol. 33, no. 5, 2019, doi: 10.1007/s12206-019-0440-9.

[17] H. Tourajizadeh and M. Rezaei, "Design and control of a steerable screw in-pipe inspection robot," In 2016 4th International Conference on Robotics and Mechatronics (ICROM), pp. 98-104. IEEE, 2016. doi: 10.1109/ICRoM.2016.7886824.

[18] T. Yamamoto, S. Sakama, and A. Kamimura, "Pneumatic Duplex Chambered Inchworm Mechanism for Narrow Pipes Driven by only Two Air Supply Lines," IEEE Robot. Autom. Lett., vol. 5, no. 4, pp. 5034–5042, 2020, doi: 10.1109/LRA.2020.3003859.

[19] K. Kusunose et al., "Development of inchworm type pipe inspection robot using extension type flexible pneumatic actuators," Int. J. Automot. Mech. Eng., vol. 17, no. 2, pp. 8019–8028, 2020, doi: 10.15282/ijame.17.2.2020.20.0601.

[20] K. Hayashi et al., "Improvement of pipe holding mechanism and inchworm type flexible pipe inspection robot," Int. J. Mech. Eng. Robot. Res., vol. 9, no. 6, 2020, doi: 10.18178/ijmerr.9.6.894-899.

[21] D. Fang, J. Shang, Z. Luo, P. Lv, and G. Wu, "Development of a novel self-locking mechanism for continuous propulsion inchworm in-pipe robot," Adv. Mech. Eng., vol. 10, no. 1, 2018, doi: 10.1177/1687814017749402.

[22] M. B. Khan et al., "ICrawl: An Inchworm-Inspired Crawling Robot," IEEE Access, vol. 8, 2020, doi: 10.1109/ACCESS.2020.3035871.

[23] M. Aliff et al., "Development of Pipe Inspection Robot using Soft Actuators, Microcontroller and LabVIEW," Int. J. Adv. Comput. Sci. Appl., vol. 13, no. 3, pp. 349–354, 2022, doi: 10.14569/IJACSA.2022.0130343.

[24] J. Yang, Y. Xue, J. Shang, and Z. Luo, "Research on a new bilateral self-locking mechanism for an inchworm micro in-pipe robot with large traction," Int. J. Adv. Robot. Syst., vol. 11, 2014, doi: 10.5772/59309.

[25] G. Feng, W. Li, Z. Li, and Z. He, "Development of a wheeled and wall-pressing type in-pipe robot for water pipelines cleaning and its traveling capability," Mechanika, vol. 26, no. 2, pp. 134–145, 2020, doi: 10.5755/j01.mech.26.2.18783.

[26] L. Brown, J. Carrasco, S. Watson, and B. Lennox, "Elbow Detection in Pipes for Autonomous Navigation of Inspection Robots," J. Intell. Robot. Syst. Theory Appl., vol. 95, no. 2, 2019, doi: 10.1007/s10846- 018-0904-7.

[27] L. Brown, J. Carrasco, and S. Watson, “Autonomous elbow controller for differential drive in-pipe robots,” Robotics, vol. 10, no. 1, 2021, doi: 10.3390/robotics10010028.

[28] M. A. A. Wahed and M. R. Arshad, “Wall-press type pipe inspection robot,” In 2017 IEEE 2nd International Conference on Automatic Control and Intelligent Systems (I2CACIS), pp. 185-190. IEEE, 2017, doi: 10.1109/I2CACIS.2017.8239055.

[29] H. Jang, T. Y. Kim, Y. C. Lee, Y. H. Song, and H. R. Choi, “Autonomous Navigation of In-Pipe Inspection Robot Using Contact Sensor Modules,” IEEE/ASME Trans. Mechatronics, pp. 1–10, 2022, doi: 10.1109/TMECH.2022.3162192.

[30] S. Savin, S. Jatsun, and L. Vorochaeva, “State observer design for a walking in-pipe robot,” MATEC Web Conf., vol. 161, no. April, 2018, doi: 10.1051/matecconf/201816103012.

[31] S. Savin, “RRT-based Motion Planning for In-pipe Walking Robots,” In 2018 Dynamics of Systems, Mechanisms and Machines (Dynamics), pp. 1-6. IEEE, 2018, doi: 10.1109/Dynamics.2018.8601473.

[32] G. H. Jackson-Mills et al., “Non-assembly Walking Mechanism for Robotic In-Pipe Inspection,” in Lecture Notes in Networks and Systems, 2022, vol. 324 LNNS. doi: 10.1007/978-3-030-86294-7_11.

[33] S. Savin and L. Vorochaeva, “Footstep planning for a six-legged in pipe robot moving in spatially curved pipes,” In 2017 International Siberian Conference on Control and Communications (SIBCON), pp. 1-6. IEEE, 2017, doi: 10.1109/SIBCON.2017.7998581.

[34] A. Zagler and F. Pfeiffer, “‘MORITZ’ a pipe crawler for tube junctions,” Proc. - IEEE Int. Conf. Robot. Autom., vol. 3, pp. 2954– 2959, 2003, doi: 10.1109/robot.2003.1242044.

[35] W. Zhao, L. Zhang, and J. Kim, “Design and analysis of independently adjustable large in-pipe robot for long-distance pipeline,” Appl. Sci., vol. 10, no. 10, 2020, doi: 10.3390/app10103637.

[36] Z. Wu, Y. Wu, S. He, and X. Xiao, “Hierarchical fuzzy control based on spatial posture for a support-tracked type in-pipe robot,” Trans. Can. Soc. Mech. Eng., vol. 44, no. 1, 2020, doi: 10.1139/tcsme-2018- 0052.

[37] M. Ciszewski, T. Buratowski, and M. Giergiel, “Modeling, Simulation and Control of a Pipe Inspection Mobile Robot with an Active Adaptation System,” in IFAC-PapersOnLine, 2018, vol. 51, no. 22. doi: 10.1016/j.ifacol.2018.11.530.

[38] A. S. Z. Abidin et al., “Development of In-Pipe Robot D300: Cornering Mechanism,” in MATEC Web of Conferences, 2017, vol. 87. doi: 10.1051/matecconf/20178702029.

[39] V. Consumi, J. Merlin, L. Lindenroth, D. Stoyanov, and A. Stilli, “A Novel Soft Shape-shifting Robot with Track-based Locomotion for In-pipe Inspection,” 2022, doi: https://arxiv.org/abs/2202.10840.

[40] A. Hadi, A. Hassani, K. Alipour, R. Askari Moghadam, and P. Pourakbarian Niaz, "Developing an adaptable pipe inspection robot using shape memory alloy actuators," J. Intell. Mater. Syst. Struct., vol. 31, no. 4, pp. 632–647, 2020, doi: 10.1177/1045389X19898255.

[41] H. Li, R. Li, J. Zhang, and P. Zhang, "Development of a pipeline inspection robot for the standard oil pipeline of china national petroleum corporation," Appl. Sci., vol. 10, no. 8, 2020, doi: 10.3390/APP10082853.

[42] S. Kazeminasab and M. Kathrine Banks, "A Localization and Navigation Method for an In-pipe Robot in Water Distribution System through Wireless Control towards Long-Distance Inspection," IEEE Access, , 9, pp.117496-117511, 2021, doi: 10.1109/ACCESS.2021.3106880.

[43] R. S. Elankavi, D. Dinakaran, R. M. K. Chetty, M. M. Ramya, A. Selvakumar, and A. Doss, "Kinematic Modeling and Analysis of Wheeled In-Pipe Inspection Mobile Robot," In: Hussain C.M., Di Sia P. (eds) Handbook of Smart Materials, Technologies, and Devices. Springer, Cham, p p. 1–15, 2021, doi: 10.1007/978-3-030-58675- 1_168-1.

[44] A. Kakogawa, Y. Komurasaki, and S. Ma, "Shadow-based operation assistant for a pipeline-inspection robot using a variance value of the image histogram," J. Robot. Mechatronics, vol. 31, no. 6, 2019, doi: 10.20965/jrm.2019.p0772.

[45] W. Zhao et al., "A coordinated wheeled gas pipeline robot chain system based on visible light relay communication and illuminance assessment," Sensors (Switzerland), vol. 19, no. 10, 2019, doi: 10.3390/s19102322.

[46] T.-J. Yeh and T.-H. Weng, "Analysis and Control of an In-Pipe Wheeled Robot With Spiral Moving Capability," J. Auton. Veh. Syst., vol. 1, no. 1, 2021, doi: 10.1115/1.4048376.

[47] F. Yan, H. Gao, L. Zhang, and Y. Han, "Design and motion analysis of multi-motion mode pipeline robot," J. Phys. Conf. Ser., vol. 2246, no. 1, 2022, doi: 10.1088/1742-6596/2246/1/012029.

[48] A. A. Bandala et al., "Control and Mechanical Design of a Multi diameter Tri-Legged In- Pipe Traversing Robot," In 2019 IEEE/SICE International Symposium on System Integration (SII), pp. 740-745. IEEE, 2019, doi: 10.1109/SII.2019.8700363.

[49] H. Sawabe, M. Nakajima, M. Tanaka, K. Tanaka, and F. Matsuno, "Control of an articulated wheeled mobile robot in pipes," Adv. Robot., vol. 33, no. 20, 2019, doi: 10.1080/01691864.2019.1666737.

[50] D. Zheng, H. Tan, and F. Zhou, "A design of endoscopic imaging system for hyper long pipeline based on wheeled pipe robot," AIP Conf. Proc., vol. 1820, pp. 1–10, 2017, doi: 10.1063/1.4977316.

[51] E. Islas‐garcía, M. Ceccarelli, R. Tapia‐herrera, and C. R. Torres‐sanmiguel, "Pipeline inspection tests using a biomimetic robot," Biomimetics, vol. 6, no. 1, pp. 1–16, 2021, doi: 10.3390/biomimetics6010017.

[52] M. Roussialian, H. Al Zanbarakji, A. Khawand, A. Rahal, and M. Owayjan,

"Design and Development of a Pipeline Inspection Robot," Mech. Mach. Sci., vol. 58, pp. 43–52, 2019, doi: 10.1007/978-3-319- 89911-4_4.

[53] R. S. Elankavi, "Developments in Inpipe Inspectionrobot: a Review," J. Mech. Contin. Math. Sci., vol. 15, no. 5, 2020, doi: 10.26782/jmcms.2020.05.00022.

[54] Y. Kwon and B. Yi, "Design and Motion Planning of a Two-Module," IEEE Trans. Robot., vol. 28, no. 3, pp. 681–696, 2012, doi: 10.1109/TRO.2012.2183049.

[55] J. H. Kim, G. Sharma, and S. S. Iyengar, "FAMPER: A fully autonomous mobile robot for pipeline exploration," Proc. IEEE Int. Conf. Ind. Technol., pp. 517–523, 2010, doi: 10.1109/ICIT.2010.5472748.

[56] Y. S. Kwon, B. Lee, I. C. Whang, W. K. Kim, and B. J. Yi, "A flat pipeline inspection robot with two wheel chains," Proc. - IEEE Int. Conf. Robot. Autom., pp. 5141–5146, 2011, doi: 10.1109/ICRA.2011.5979712.

[57] M. S. Mohd Aras et al., Design and development of remotely operated pipeline inspection robot, In Proceedings of the 11th National Technical Seminar on Unmanned System Technology 2019, pp. 15- 23, 2021, doi: 10.1007/978-981-15-5281-6_2.

[58] Y. Zhang and G. Yan, "In-pipe inspection robot with active pipe diameter adaptability and automatic tractive force adjusting," Mech. Mach. Theory, vol. 42, no. 12, pp. 1618–1631, 2007, doi: 10.1016/j.mechmachtheory.2006.12.004.

[59] L. Xu, L. Zhang, J. Zhao, and K. Kim, "Cornering algorithm for a crawler in-pipe inspection robot," Symmetry (Basel)., vol. 12, no. 12, 2020, doi: 10.3390/sym12122016.

[60] E. N. P. M. K. N. Karuppasamy, "Defect identification in pipe lines using," Int. J. Mech. Eng. Robot. Res., vol. 1, no. 2, pp. 19–31, 2012.

[61] W. C. Chang, Y. C. Huang, and P. Y. Chang, "Development of a 3D pipe robot for smart sensing and inspection using 3D printing technology," Smart Sci., vol. 5, no. 3, 2017, doi: 10.1080/23080477.2017.1338428.

[62] R. S. Elankavi, D. Dinakaran, A. S. Arockia Doss, R. M. Kuppan Chetty, M. M. Ramya, "Design and Motion Planning of a Wheeled Type Pipeline Inspection Robot", Journal of Robotics and Control (JRC) Vol. 3, No. 4, pp. 415-430, July 2022.

[63] M. A. Baballe, U. Y. Magashi, B. I. Garko, A. A. Umar, Y. R. Magaji, M. Surajo, "Automatic Gas Leakage Monitoring System Using Mq-5 Sensor", Review of Computer Engineering Research, Vol. 8, No. 2, pp. 64-75, DOI: 10.18488/journal.76.2021.82.64.75, 2021.

[64] M. A. Baballe, M. I. Bello, A. S. Mahmoud, "Comparative Study of Gas Alarm Detection System", Journal of Telecommunication Control and Intelligent System (JTCIS), Vol. 1, No. 2, pp. 65-72, 2021.

[65] M. A. Baballe, M. I. Bello, "Gas Leakage Detection System with Alarming System", Review of Computer Engineering Research, Vol. 9, No. 1, pp. 30-43, DOI: 10.18488/76.v9i1.2984, 2022.

[66] M. B. Ahmad, A. S. Muhammad, “A general review on advancement in the robotic system”, Artificial & Computational Intelligence, vol. 1, no. 2, pp. 1-7, http://acors.org/ijacoi/VOL1_ISSUE2_04.pdf, Mar 2020.

[67] M. Çavaş, M. B. Ahmad, “A Review on Spider Robotic System”, International Journal of New Computer Architectures and their Applications (IJNCAA) vol. 9, no. 1, pp. 19-24, The Society of Digital Information and Wireless Communications, 2019.

[68] https://www.pipedetect.com/the-principle-and-advantages-of-using-robots-for-ndt-pipeline-inspection.html.