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A Review on Wheeled Type In-Pipe Inspection Robot

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***Abstract*—Research in In-Pipe Inspection Robots (IPIRs) has gained interest over recent years. Pipeline inspection robots bring reliability and repeatability to various pipeline inspection and maintenance processes. IPIRs are categorized based on their type of locomotion, and this study aims to analyze their advantages and limitations. Among all the IPIRs, the wheeled type IPIR has seen a tremendous change in its design, steering mechanism, and the way they use different wheels to pass through pipelines easily. This study compares and analyses an up-to-date review on wheeled type IPIRs in detail. This review helps the researchers to select the optimal wheeled type IPIR for inspection. The review concludes with the future research directions that the researchers need to focus on for the development of pipeline inspection robots. Developing an effective IPIR ensures human safety and improves the inspection process.**

***Index Terms*— pipeline inspection robot, mobile robot, motion, steering mechanism, wheeled type**

I. INTRODUCTION

The Pipeline Inspection Robot system is one of the vastest research domains in robotics. The world still uses pipelines to transfer liquids and gases because it acts as a safer alternative than other modes of transport [1]. However, the pipelines tend to deteriorate over time due to their mundane transportation task; thus, they need periodic monitoring to work effectively [2], [3]. If pipelines are not properly maintained, they might leak, resulting in fatal accidents and pollution [4]. Humans inspect pipelines, and the recent technological developments made robots effective for inspecting pipelines [5]. In-Pipe Inspection and Out-Pipe Inspection are the two types of the robotic-based pipeline inspection method. The Out-Pipe Inspection is more convenient for inspection than the In-Pipe Inspection since we do not have to stop the flow of any medium inside the pipeline during inspection [6]. Since humans were inspecting inside potentially hazardous pipelines, developing an effective IPIR would improve human safety. IPIR uses different types of locomotion to manoeuvre inside the pipeline. The most used types among them are the Pipeline Inspection Gauge (PIG) type [7]–[11], leg type [12]–[15], caterpillar type [16]–[20], wheel type [21]–[26], wall-press type [27]–[31], inchworm type [32]–[36] and screw-type [37]–[42] as shown in Fig. 1. Each category has its own set of benefits and limitations [43].

A. Types of IPIR

The PIG type utilises a launcher and receiver to move inside the pipeline under fluid pressure [7]–[11]. The walking or legged type uses legs, and these legs mimic the movement of a leg to walk inside the pipeline [12]–[15]. The caterpillar type moves inside pipelines on tracked wheels, enabling them to maintain contact with the pipeline's inner surface under variable conditions [16]–[20]. The wheeled type robot is simple in mechanism and uses wheels to move in the pipeline [21]–[26]. The wall-press type uses the contact force between the robot and pipeline surface to move in the pipeline [27]–[31]. The inchworm type uses the robot's gripping force to move through the pipeline [32]–[36]. The screw-type robot has wheels inclined at an angle to replicate the motion of a screw to move inside a pipeline [37]–[42]. Each category has its own set of benefits and limitations [44].

The PIG type struggles to turn at sharp bends. The screw-type has a complex steering mechanism and finds difficulty in back driving. The inchworm type has less traction force than the other types. The wall-press type has high friction that can harm the pipeline structure and is challenging to steer, and the walking type has a complicated mechanism and gets stuck when the mechanism fails. As a result, of all the types, the wheeled type IPIR is best suited for in-pipeline inspection because they only have a traditional limitation of pipe slippage, which is kept under control by appropriate design and development [43].

This paper focuses on wheeled type In-Pipe Inspection Robots and their application in various pipeline inspections. Even though the screw-type employs wheels, it does not fall under the wheeled type. Hence it will not be discussed in this review.

In comparison to other types of in-pipe robots, the wheeled in-pipe inspection robot has the following advantages: It is simple in mechanism, there is less friction between the robot and pipe wall, mobility inside the pipeline is high, and crawls through horizontal, vertical, curved, branched and varying diameter pipes, it back-drives with ease, lighter and smaller robot is achievable through proper design, manoeuvers through

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pipelines with a lesser inner diameter starting from 40 mm, overcomes obstacle inside pipelines, it is modular in design, and there are possibilities to employ different types of wheels, etc.,.

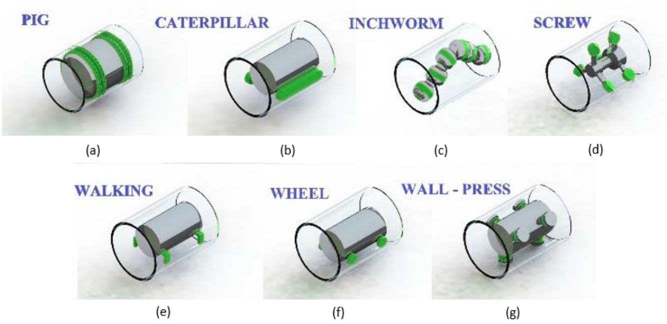

Figure 1. Different In-Pipe Inspection Robots [44] : (a) PIG, (b) Caterpillar, (c) Inchworm, (d) Screw, (e) Walking, (f) Wheel, (g) Wall-Press.

The structure of this article is presented as follows. Section 2 discusses about the different types of wheels and locomotion available in wheeled type IPIR. Section 3 discusses the different steering mechanisms used in wheeled type IPIR. The findings and discussion are presented in section 4, and section 5 concludes the review with future research directions.

II. LOCOMOTION TYPES USED IN WHEELED TYPE IN-PIPE INSPECTION ROBOT (IPIR)

Wheels are circular items that reduce friction, wear, and tear on the surfaces they travel over [45]. Fig. 2 illustrates the types of wheels and the functions they perform. All the different types of wheels mentioned in Fig. 2 are capable of being active or passive wheels. The number and type of wheel used are essential in deriving the kinematic and dynamic model of the robot. Fig. 3 shows the different types of wheels used in pipeline robot.

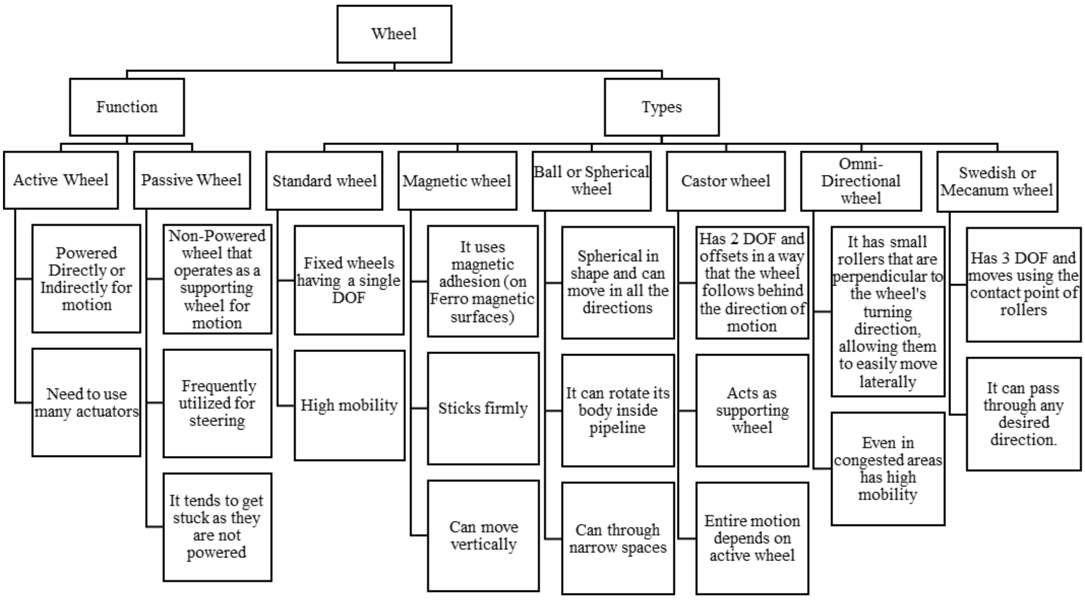

Figure 2. Classification of wheels based on their use in pipeline robots.

The wheeled type IPIR uses two types of motion one is the wheeled motion, and the other is the hybrid motion. The wheeled motion, like the wheeled mobile robot, uses the motion of wheels to pass through the pipelines. The hybrid motion combines the wheeled type locomotion and the wall-press type locomotion available in the IPIR locomotion type to pass through the pipeline. The hybrid locomotion type enables the robot to overcome all the limitations faced by all other locomotion types in IPIR. The following section discusses how the wheeled IPIR moves through straight (horizontal and vertical), curved, and pipes of varying diameters.

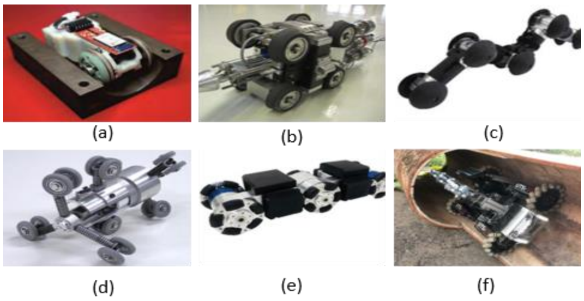

Figure 3. Different types of wheels used in pipeline robot.: (a) Magnetic wheel [46], (b) Standard wheel [47], (c) Spherical wheel [5], (d) Castor wheel [5], (e) Omni-Directional wheel [5], (f) Mecanum wheel [48].

A. *Wheeled Locomotion*

Fig. 4 shows the prototypes of robots using standard and magnetic wheels. The wheeled type IPIR uses the standard wheels to move forth and back inside the pipelines [49]. This robot works like a wheeled mobile robot, except that it moves inside the pipeline. The robot's disadvantage is that it cannot climb vertical pipes, and when it tries to climb inside vertical pipes, it fails and slips inside the pipeline due to gravity and lack of support. Magnetic wheels help to get around this limitation. The robot uses magnetic adhesion from magnetic wheels to crawl inside vertical pipelines [50]. The limitation of magnetic wheeled robots is that they can only climb vertically in ferromagnetic pipes.

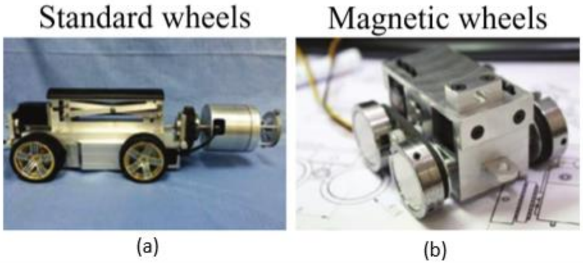

Figure 4. Robots using: (a) standard wheels [49] and (b) magnetic wheels [50].

B. *Hybrid Locomotion*

1) *Two wheeled wall-pressed type IPIR*

The two-wheeled wall-pressed type IPIR uses two wheels placed symmetrically at an angle of 180 degrees apart from each other, as shown in Fig. 5. It reduces the area occupied by the robot inside the pipeline. This robot uses a two-wheel chain mechanism to move inside the pipeline [51]. The two-chain mechanism pushes the two wheels against the inner surface of the pipeline to gain stability for moving inside the pipeline.

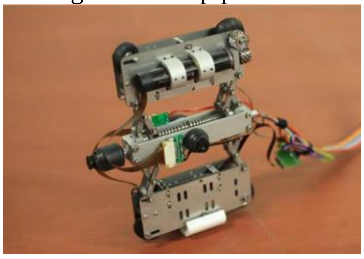

Figure 5. Two wheeled wall-pressed type IPIR [51].

2) *Three wheeled wall-pressed type IPIR*

The three-wheeled wall-pressed type IPIR is one of the most used types of hybrid locomotion. It is the combination of wheeled type and wall-press type, as shown in Fig. 6. The three-wheeled wall-pressed IPIR uses three wheels placed at an angle of 120 degrees symmetrically apart from each other [52]–[54] to crawl through the pipelines. The robot uses spring [52], adaptive linkage [53], four-bar [54], five-bar [54] and parallelogram [54] to make the arm adjust according to the inner shape and diameter of the pipeline. The three wheels press against the inner surface of the pipeline to stabilize themselves and move inside the pipeline. In this type of design, there is a possibility of motion singularity (loss of contact between robot and pipe) [55] occurring inside pipelines.

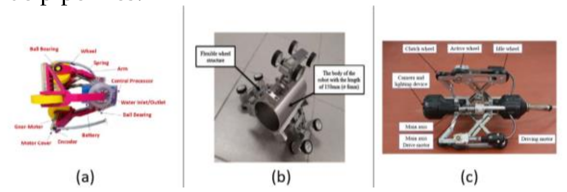

Figure 6. Prototypes of three wheeled wall-pressed type IPIR. (a) Spring Mechanism [52], (b) Adaptive Mechanism [53], (c) Four-Bar, Five-Bar and Parallelogram Mechanism [54].

3) *Supporting wheeled type IPIR*

The wheeled type IPIR that uses standard wheels to crawl inside the pipelines adds a supporting wheel on the top of the robot to form the supporting wheeled type IPIR, as shown in Fig. 7. This type overcomes the limitations of wheeled type IPIR, which cannot climb vertical pipes and can only pass through horizontal and slightly inclined pipelines [56]. The robot uses springs to make the supporting wheels touch the inner surface of the pipelines [56], [57]. This support helps the robot to move through horizontal and vertical pipelines. The limitation of this design is that it is difficult to pass through branched pipes.

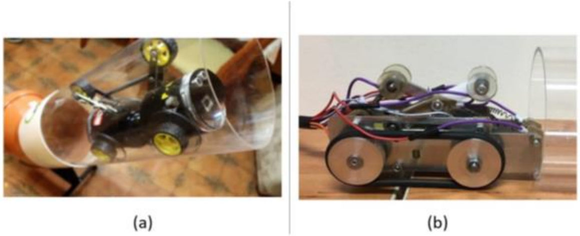

Figure 7. Prototypes of supporting wheeled type IPIR. (a) Semi-Autonomous Robot [56], (b) PIRSMA [57].

4) *Multilink-Articulated wheeled type IPIR*

The articulated wheeled type IPIR employs the robot's joints to form a V-shape so that the wheels at the end of the joints press against the pipeline's inner surface, as seen in Fig. 8. This shape helps the robot crawl through the pipeline with a body bent like an inchworm [58]. The robots use motor-actuated joints and torsion springs to form a V-shape structure that allows them to clamp inside pipelines [58]–[60]. Its limitation comes when the inner diameter of the pipeline increases, as this type of robot requires an increase in the length and number of drives used to form a V-shape so that it can gain stability for motion in vertical pipes.

Figure 8. Prototypes of articulated wheeled type IPIR. a) AIRo [58], b) PIRATE [59].

5) *Bio-inspired wheeled type IPIR*

These robots are biologically inspired by spiders [61], inchworms and snakes [62], as shown in Fig. 9. Islas-García E. et al. [61] developed a robot imitating a spider, and it uses springs to imitate the motion of spider legs by making the wheels touch the inner surface of the pipeline during motion. L. Pfotzer et al. [62] developed a snake-like robot that can alter the angle of joints present in the robot; this helps the robot to pass over the obstacles easily like a snake, and this robot can pass through pipelines having a minimum diameter of 250 mm. These bio-inspired types of IPIR are commonly used in small inner diameter pipes and are not used in larger inner diameter pipes greater than 400 mm.

Figure 9. Prototypes of Bio-Inspired wheeled type IPIR. (a) Inspired by Spiders [61], (b) Inspired by Inchworms and Snakes [62].

III. STEERING MECHANISMS USED IN WHEELED TYPE IN-PIPE INSPECTION ROBOT (IPIR)

The pipelines contain straight and bent pipes, which the robot must navigate through. The L-branch, Y-branch, and T-branch are the most used pipeline joints and bends [43]. The robots must use a steering system to navigate through the bends and joints to get around this obstacle. The following section discusses the different steering mechanisms used in wheeled In-Pipe Inspection Robots (IPIR).

A. *Differential Steering*

Se-gon Roh and Hyouk Ryeol Choi [63] developed a differential steering drive robot that can pass through a branched pipeline by varying the speed of the robot wheels, as shown in Fig. 10—turning the robot around its centre axis results in the other differential steering method. If the robot wants to turn right, rotate the left wheel clockwise and the right wheel anti-clockwise [44]. The robot must have three wheels or more to perform differential drive steering in vertical pipes. Fig. 11 shows the differential steering of the robot inside the L-branch pipe.

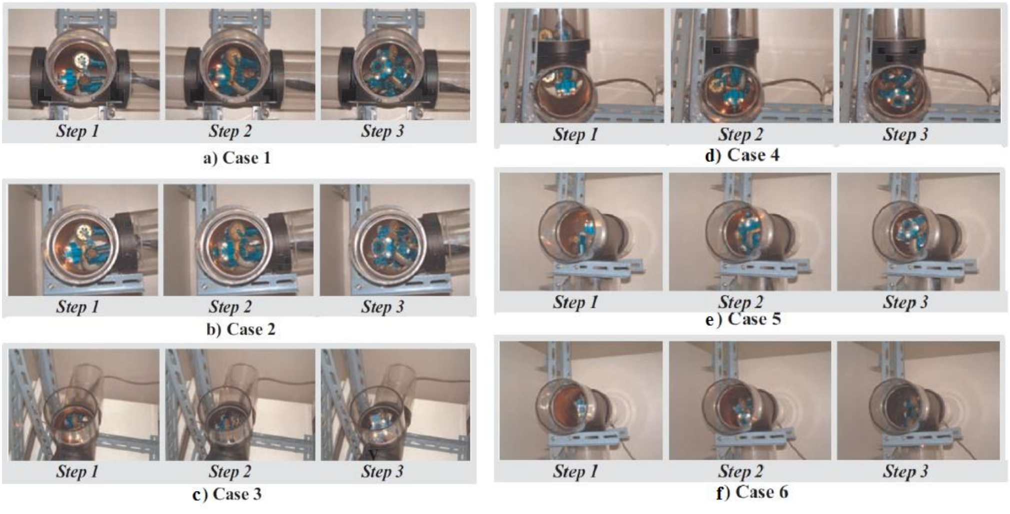

Figure 10. Navigation of robot inside branches for six different cases [63], Case 1: Robot steering in straight T-branch pipe, Case 2: Robot steering in inclined T-branch pipe, Case 3: Robot steering in T-branch (horizontal to vertical plane), Case 4: Robot steering in T-branch (vertical to horizontal plane), Case 5: Robot steering left in T-branch (vertical to horizontal plane), Case 6: Robot steering right in T-branch (vertical to horizontal plane).

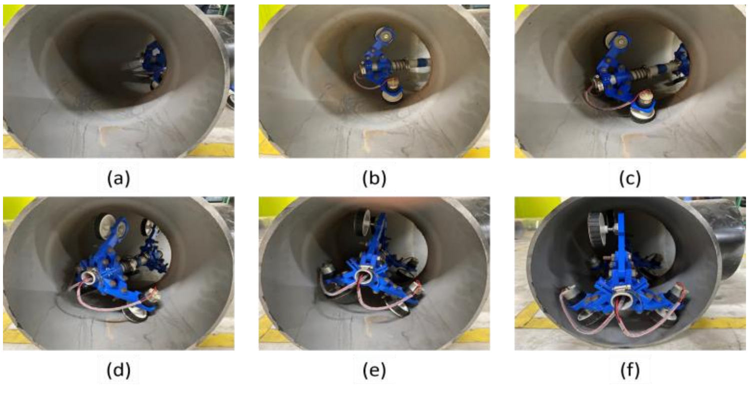

Figure 11. Differential steering of robot inside L-branch pipe [44], Robot: (a) Enters L-branch pipe, (b) Moves forward inside, (c - d) Robot steers left using differential steering around its centre axis, (e) Moves forward, (f) Exits L-branch pipe.

B. *Wheel Steering*

Young-Sik Kwon et al. [51] developed a wheel steering robot to steer across branched pipelines while maintaining the same motor speed. An active wheel, an idle wheel, a steering motor, and a steering mechanism work together to provide this steering. Here, the steering motor causes the wheel to turn in the appropriate direction, allowing the robot to navigate through branched pipes easily. Fig. 12 shows the wheel steering of the robot inside the T-branch pipe.

C. *Articulated Steering*

Articulated robots are Robots with two or more linked joints. The steering mechanism used by them to pass through pipelines is called articulated steering. These articulated robots use two types of steering mechanisms: rolling body steering and active joint steering.

1) *Rolling body steering*

Atsushi Kakogawa & Shugen Ma [58] developed a multilink-articulated robot with a body that rolls in the pipe's circumferential direction, which helps the robot navigate inside branched pipes by guiding it in the right direction. Omnidirectional, hemispherical wheels do this steering. The hemispherical wheels rotate first, allowing the omnidirectional wheels in contact with the pipe's inner surface to rotate in the same direction as the hemispherical wheels, causing the robot to rotate. This rolling causes the robot's front clamped side to arrange itself in the desired turning direction it must steer and then moves forward. Fig. 13 shows the rolling body steering of the robot inside the T-branch pipe.

2) *Active joint steering*

MRINSPECT III [64] uses a Double Active Universal Joint (DAUJ) [65] steering mechanism to pass through branched pipes. For omnidirectional steering, this active joint has an upper and lower sphere. It uses the combination of two half-spheres to accomplish the desired joint rotation with the help of motors [65]. Fig. 14 shows the robot's navigation inside the branch pipe using active joint steering.

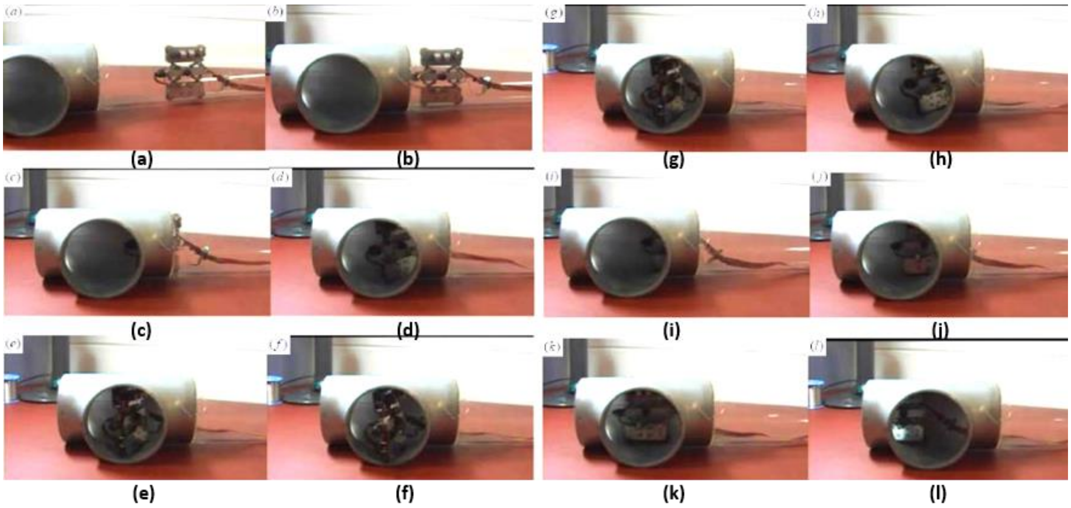

Figure 12. Wheel steering of robot inside T-branch pipe [51], Robot: (a-c) Moving forward inside straight pipeline, (d-f) Wheel steering of robot to the left direction, (g-i) Moving backward inside T-branch pipe, (j-l) Moving forward straightly inside T-branch pipe without wheel steering.

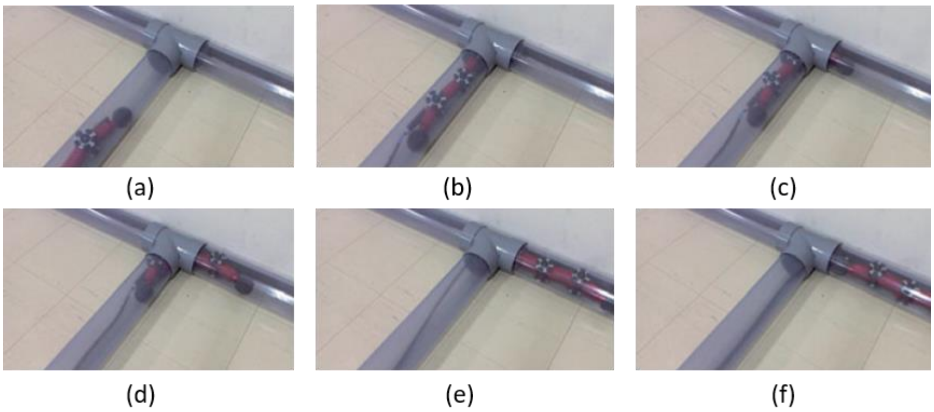

Figure 13. Rolling body steering of robot inside T-branch pipe [58], Robot: (a) Moves forward inside straight pipeline, (b) Enters T-branch pipe, (c-d) Steers right using rolling body steering, (e) Exits T-branch pipe, (f) Moves forward inside straight pipeline after exiting T-branch pipe.

The performance and specifications of all the wheeled type IPIRs studied in this paper are summarized in Table I. In the table, H denotes Horizontal pipe, V denotes Vertical pipe, C denotes curved pipe, T denotes T-

Branched pipe, and VDP denotes Variable diameter pipe. If the robot satisfies the above conditions, it is given a (✓) symbol, and if it does not, it is given a (×) symbol.

IV. FINDINGS AND DISCUSSION

It is seen from the review that the wheeled type IPIRs are classified based on their locomotion types. They are the wheeled locomotion type and the hybrid locomotion type. The wheeled locomotion type consists of robots using standard wheels and magnetic wheels. It reveals that robots with standard wheels cannot climb vertical pipes, whereas robots with magnetic wheels can, but only in ferromagnetic pipes.

The hybrid locomotion type has two-wheeled and three-wheeled wall-pressed type robots which can pass through all pipeline junctions, including curved and branched pipes. There are robots with four, and six-wheeled configurations in the wheeled wall-pressed type. This review contains two- and three-wheeled wall-pressed type robots, the most widely used types. The supporting wheeled-type robots can pass through vertical pipes but struggle to steer through branched pipes. The multilink-articulated type can pass through pipes with a lesser diameter and accommodate pipes of varying diameters. They can also pass through curved and branched pipes. The bio-inspired type is still under development because robots that can move inside horizontal and vertical pipes cannot move in branched pipes, and robots that can move in branched pipes cannot climb vertical pipes.

Regarding branched pipes, each robot uses a different mechanism to steer. The wheeled wall-pressed types use differential steering and wheel steering. The multilink-articulated type and bio-inspired type use articulated steering.

Among them, the multilink-articulated wheeled type and wheeled wall-pressed type are commonly used because they can manoeuvre inside all pipeline junctions. Since the articulated type can only be used for visual inspection as it cannot carry a high payload to do an inspection using other NDT methods, the wheeled wall-pressed type is preferred. Hence, the most dominant among the wheeled type IPIR is the wheeled wall-pressed type IPIR.

The robot using a standard wheel cannot pass through vertical and branched pipes, and the two-wheeled wall-pressed type has a complex mechanism and requires a skilled person to operate. Hence, these two types are phased out

In recent years [44], [52], [53], the wheeled wall-pressed type is becoming more prominent than the other wheeled type IPIRs. The use of wheeled wall-pressed type in China is also evident in [22].

(a) (b)

Figure 14. Active joint steering of robot in branch [64], (a) Steering inside T-branch, (b) Moves straightly inside T-branch without steering.

TABLE I. SUMMARY OF SPECIFICATIONS AND APPLICATIONS OF WHEELED TYPE IPIR

Robot Details					**Applications**								**Authors**	**Limitations**
Mechanism	**Type of control**	**Length (mm)**	**Weight (kg)**	**Nominal inner pipe Diameter (mm)**	**Types of Application**	**Mobility**	**H**	**V**	**C**	**T**	**VDP**	**Can Overcome Obstacles**		
I Articulated Steering	**Manual**	**550**	**1.7**	**100**	**Not Specified**	**High**	✓	✓	✓	✓	✓	**Yes**	**Atsushi Kakogawa et al. (2018)** [58]	**Length of the robot and the number of actuators used increases with the increase in inner pipeline diameter**
	Autonomous	**NA**	**NA**	**150**		**High**	✓	✓	✓	✓	✓	**Yes**	**Geerlings, N. M. et al. (2018)** [59]	
		1800	**47**	**250**		**High**	✓	✓	✓	✓	✓	**Yes**	**L. Pfotzer et al. (2015)** [62]	

II Differential-Drive Mechanism	**Manual**	**150**	**0.7**	**97**	**Gas Pipelines**	**High**	✓	✓	✓	✓	✓	–	**Se-gon Roh and Hyouk Ryeol Choi (2005) [63]**	**Motion singularity is not in the scope of study**
II Differential-Drive Mechanism	**Manual**	**79.7**	**1.4**	**130**	**Ferromagnetic Pipeline**	**Moderate**	✓	✓	✓	✓	✓	**Yes**	**Md Raziq Asyraf Md Zin et al. (2012) [50]**	
		122	**0.2**	**100**	**Not Specified**	**High**	✓	✓	✓	✓	✓	–	**Young-Sik Kwon et al. (2010) [54]**	**Possibility of motion singularity inside pipelines.**
III Magnetic wheel	**Manual**	**85.1**	**0.1**	**50**	**Bore Pipelines**	**Moderate**	✓	✓	✓	✓	✓	–	**George H Mills et al. (2018) [46]**	**Can only climb vertically in ferromagnetic pipes**
III Magnetic wheel	**Manual**	**78**	**0.1**	**45**	**Boiler Tube**	**Moderate**	✓	✓	–	–	–	–	**Jalal et al. (2015) [66]**	**Can only climb vertically in ferromagnetic pipes**
IV Wheel Steering	**Manual**	**94**	**0.2**	**90**	**Not Specified**	**High**	✓	✓	✓	✓	✓	–	**Young-Sik Kwon et al. (2011) [51]**	**Complicated steering mechanism**
V NA	**Manual and Autonomous**	**NA**	**300**	**1330**	**Oil Pipeline**	**Moderate**	✓	×	✓	×	✓	**Yes**	**Hui Li et al. (2020) [22]**	
V NA	**Manual**	**320**	**NA**	**150**	**Hyper Long Pipeline**	**High**	✓	×	×	×	✓	–	**Dongtian Zheng et al. (2017) [49]**	**Pipeline surface may be damaged due to high friction force**
		150	**2.2**	**250**	**Not Specified**	**High**	✓	×	✓	×	✓	–	**Mohd Shahrieel Mohd Aras et al. (2021) [53]**	**High chances to lose stability**
		87	**0.3**	**75**		**Moderate**	✓	✓	✓	×	✓	–	**Alireza Hadi et al. (2020) [57]**	**Due to point contact of wheels, it sometimes loses contact with the inner pipeline surface**
		269	**NA**	**90**	**PVC Pipes**	**Moderate**	✓	✓	×	×	✓	**Yes**	**Elizabeth Islas-García et al. (2021) [61]**	

Key:

NA – Not Available

*H – Horizontal Pipe

*T – T-Branch Pipe

*C – Curved Pipe

V. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The IPIRs are classified based on their locomotion types, and among them, the wheeled type IPIR is popular because of its simplicity. The benefits of the wheeled type over other types of IPIR have attracted the attention of researchers in recent decades. A comprehensive review of the wheeled IPIR and its design, motion, steering mechanism, and behaviour inside the pipelines is presented. This review helps the researchers and maintenance personnel's to understand and select appropriate robotic systems for inspection.

The wheeled IPIR can pass through horizontal, vertical, inclined, curved, branched and varying diameter pipelines. It has high mobility, a simple mechanism, less traction, is easy to back drive, and is lighter and smaller. It is seen from the summary that the Differential-Drive Mechanism is the best suited for steering through branched pipes. The weight of the magnetic wheeled robot is lesser when compared to the other wheeled types. However, due to its limitation, the three-wheeled wall-pressed IPIR is the best suitable for passing through pipelines in terms of payload, mechanism and steering through branched pipes.

The wheeled type IPIR developed to date is used for inspecting pipelines with inner diameter above 40 mm because of sizing issues in actuators and drive systems. Micro robots should be developed to inspect pipelines with inner diameters lesser than 30 mm, and the robot's autonomous capability should also be improved. The robot using magnetic wheels has many advantages but is restricted to ferromagnetic pipes. There are few studies on the magnetic wheeled robot, and industries use ferromagnetic pipes, so there is room for improvement. The review shows that the multi-link articulated robot should decrease the number or select the proper actuator to decrease the length of the robot. It is seen that the wheeled wall-pressed type faces motion singularity, and this is not in the scope of the study. The robots developed in recent years are entirely focused on inspection. The navigation of wheeled type IPIR in the branched pipe should be studied effectively, and their improvement in design, development, simulation and performance should be seen in the near future.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Rajendran Sugin Elankavi conducted the research and wrote the paper; D. Dinakaran, R. M. Kuppan Chetty and M. M. Ramya supervised the work; D. G. Harris Samuel helped in proofreading and enhancing the level of paper presentation; all authors had approved the final version.

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