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Review

Adapting Mechanisms for In-Pipe Inspection Robots: A Review

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Abstract: In-pipe inspection robots have proven useful in examining the inside of pipes without affecting their structure, therefore, the interest in researching these robots has constantly increased over time. There are many different types of inspection robots, but the most commonly used are the wall pressed type. This paper proposes a review of the wall pressed type inspection robots in terms of adapting mechanisms. By adapting mechanism is meant a simple linkage or a combination of linkages, with an active or passive force generation system used to adapt the robot to variations in pipe diameter. The characteristics of the different adaptation mechanisms are compared and analyzed regarding the type of linkages used, how the pressure force on the pipe wall is obtained, and the possibility of ensuring the movement through inclined or vertical pipes with elbows and branches.

Keywords: planar linkages; adapting mechanisms; in-pipe inspection; wall pressed robots

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1. Introduction

Pipe networks are a consequence of the increasingly intense development of today's society. The various problems that occur due to aging, corrosion, and cracks in the pipe walls have led to an increase in inspection, maintenance, and repair activities. Many sections of pipes are found underground, which makes access inside them even more difficult. Therefore, the use of robots for pipe inspection and/or maintenance is currently one of the most effective solutions. Their practicality proves to be even more important when the areas to be inspected are dangerous or difficult to access. Inspection robots are electromechanical devices that can move through the pipe and provide visual information and can identify various defects, or corrosion processes, thus they can provide solutions to specific problems.

The simplest classification divides these robots into two main categories: passive robots that do not have traction systems, respectively active robots that benefit from their own traction system that ensures their movement through the pipe.

Pipe networks with straight sections and relatively large and constant diameters can be easily inspected using so-called Pipeline Inspection Gauges or PIGs [1]. These inspection devices do not have their own propulsion system, so they are transported inside the pipes by the fluid flow. Pipeline inspection using these devices is accomplished by inserting a PIG into the pipe through a launcher hatch. Then the pipeline pressure pushes the PIG out of the launcher and along the pipeline until it reaches a receiver trap, on which it gets latched [2,3]. Therefore, PIGs are uncontrollable and unable to adapt to sudden changes in pipe direction and/or diameter. Despite these inconveniences most of the pipelines carrying natural gases, petrol or water can be inspected with PIGs. According to [1] these represent approximately 99% of the total existing pipelines.

Inspection of fluid-free pipelines or those which have changes in diameter and/or orientation involves the use of robots equipped with their own traction systems. The use of the active in-pipe inspection robots has led to numerous challenges regarding their design and functionality. These include but are not limited to the autonomy of the robot, the traction systems, and the mechanisms they use to adapt to variations in pipe diameter.

Depending on the method used to move inside the pipe, active inspection robots can be classified as follows: Wheel/track type [4–8], Wall pressed type [9–12], Walking type [13,14], Inchworm type [15,16], Screw type [17,18], Snake type [19,20].

The wall pressed type is the most used category of inspection robots. They usually use linkages operated passively using springs or actively using actuators. Actuation by means of springs has the advantage of constructive simplicity and allows a smooth adaptation to the change of pipe diameter. Instead, it does not allow the control of the pressing force against the pipe wall, consequently, the movement through inclined or vertical pipes can be a problem. The pressing force can be controlled using an actuator, so the robots can adapt to the inner surface of the pipe or to its orientation, therefore their movement inside the pipe becomes more efficient. This category of robots can have two, three or more chains of wheels/tracks evenly distributed around the center axis, depending on the design chosen for the robot.

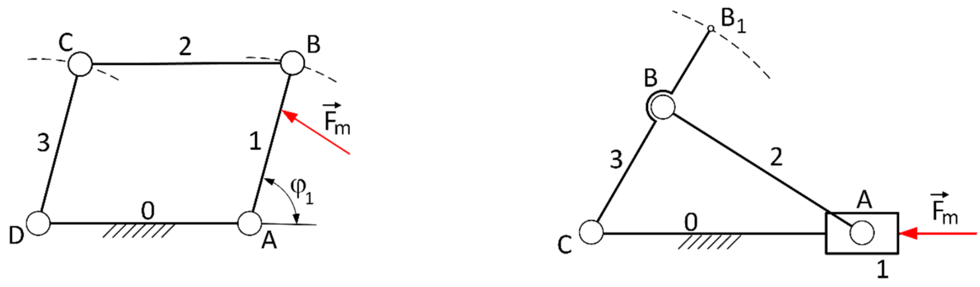
In recent years several researchers have studied various types of linkages used to adapt the robot to variations in pipe diameter, e.g., Chen et al. in [21,22], and Ciszewski et al. in [23]. There are also various reviews related to the design of the in-pipe inspection robots. Mills et al. present a review of wall pressing robots used in the inspection of unpiggable pipelines [1]. Shukla et al. present the state-of-the-art robotic solutions used in the onshore oil and gas industry [3]. Ab Rashid et al. provide an extensive review of various approaches in the modelling of the in-pipe inspection robots [24]. Ren et al. present a detailed study related to the structure, driving principles and mechanical behaviors of the Screw Drive In-Pipe Robots [25]. Verma et al. proposed a review of in-pipe inspection robots with an emphasis on the design specifications and features of each type of robot [26]. Several authors also focused on the study of locomotion for inspection robots, e.g., Siquera et al. in [27], Roslin et al. in [28] and Satheesh Kumar et al. in [29].

To the best of the authors' knowledge, there is no review of the inspection robots in terms of adapting mechanisms. By adapting mechanism is meant a simple linkage or a combination of linkages, with an active or passive force generation system and possibly a suspension system for the wheel/track. While passive adaptation mechanisms use only spring-generated force, active ones can incorporate an algorithmic adaptation in a control system. Usually, conventional control algorithms such as PID or Fuzzy are used in order to actively compensate for the traction force variations and avoid slippage. Furthermore, neural networks can be implemented to computationally incorporate adaptation into the control loop [30,31].

2. Linkages for Adapting Mechanisms

There are many types of linkages that can theoretically be used to increase the pressure between the drive wheels/tracks and the pipe wall. Regardless of their structure and type, they must ensure that the robot adapts as easily as possible to variations in the diameter of the pipe. Furthermore, it must provide a constant and sufficient pressure to allow the robot to move. For many categories of in-pipe inspection robots, the linkages used for adapting mechanisms actually determine their mechanical structure and size. Therefore, the type of linkage used and the correct way of designing it can significantly change the performance of the robot.

The adapting mechanism should have a small number of elements, reduced complexity and take up as little space as possible inside the pipe. From this standpoint, the majority of them have as base units, the four-bar and slider-crank linkages shown in Figure 1.



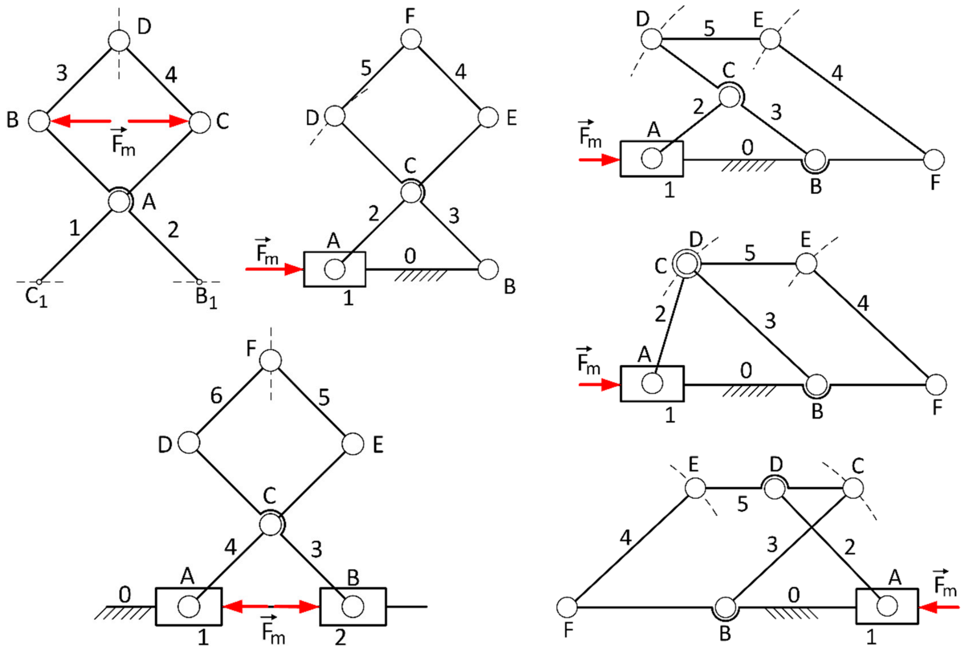
(**a**) (**b**)

Figure 1. Base units for adapting mechanisms: (**a**) four-bar linkage; (**b**) slider-crank linkage.

These are simple and planar linkages with 1 DOF consisting of three mobile elements and four lower pair revolute and/or prismatic joints. In all the following schematic diagrams, the mobile elements of the linkages are denoted by numbers starting from *1*, and the joints with the letters *A*, *B*, etc. The movements of the linkage's elements are relative to an element denoted by *0*. A force, denoted by $\vec{F}_m$, produced by a spring or an actuator can be applied on element *1* to move the rest of the elements in the linkage.

In order to adapt to the diameter of the pipe and to improve the stability of the movement, the axial dimension of the mechanism is usually larger than the cross dimension. In most cases, the force required to adapt the robot to the inside diameter of the pipe is applied in the axial or near axial direction. This ensures a higher applied pressure on the pipe wall and a sufficient linear displacement at the point of application of the force. Therefore, taking the four-bar linkage as the base unit to design the adapting mechanism, a slider-crank linkage can be added to it. According to [21], 14 topological combinations are possible between the two base units shown in Figure 1.

The input of the horizontal displacement should be small to reduce the size of the adapting mechanism and the output of the vertical displacement should be as large as possible to increase the diameter adjustment capability. A few possible configurations of linkages used for adapting mechanisms are shown in Figure 2.



(**a**) (**b**)

Figure 2. Linkages used for adapting mechanisms: (**a**) pantograph-based; (**b**) combined linkages.

Linkages shown in Figure 2 will be analyzed in this paper. Being that the topic is quite broad, the authors chose only those configurations that appear more frequently in relatively recent articles.

Several prototypes of wall pressed inspection robots developed by the authors are presented in Figure 3. Adapting the structure of the robots to the inner surface of the pipe is conducted passively, using pre-stressed compression springs.

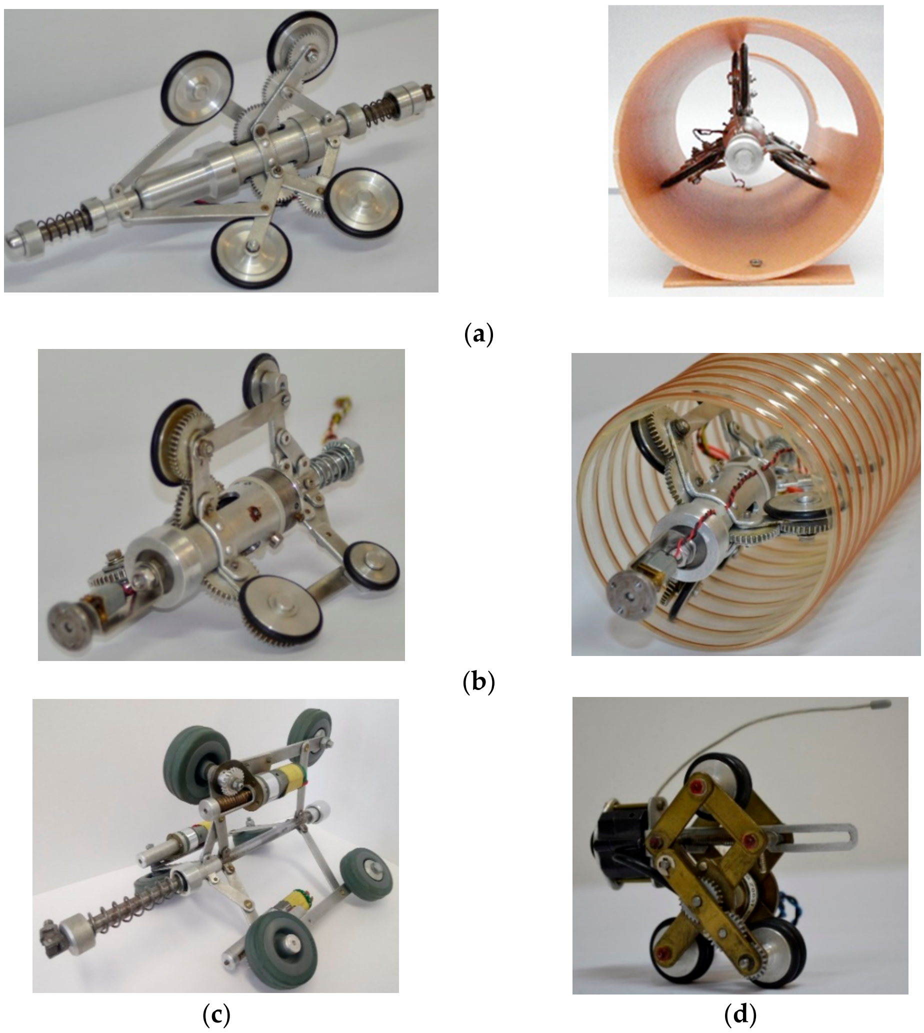


Figure 3. Prototypes of wall pressed robots designed and manufactured by authors. (**a**) Prototype based on slider-crank linkage; (**b**) prototype based on a combined linkage; (**c**) prototype based on a combined linkage with three gearmotors; and (**d**) prototype based on a pantograph linkage.

In all prototypes shown in Figure 3a,b,d, the movement along the pipe is ensured using a single drive motor. Its torque is transmitted to the drive wheels by means of gears. Alternately, for the prototype shown in Figure 3c, there is one gearmotor for each drive wheel. This slightly complicates the motion control system but increases the traction force and ensures better adaptability of the robot, especially when moving through curved pipes.

3. Analysis of Adapting Mechanisms

This section summarizes several types of adapting mechanisms for in-pipe inspection robots with several types of locomotion in terms of structure, how the pressure force on the pipe wall is obtained, the range of diameters that can be inspected, the possibility of ensuring movement through inclined or vertical pipes and overall dimension of the mechanism and robot where available.

One of the most important issues in designing a wall pressed inspection robot is ensuring sufficient traction force to pull the robot itself and any auxiliary tools or devices through the pipe. The traction force is proportional to the friction coefficient and the pressure force between the drive wheel/track and the pipe surface. The friction coefficient is usually variable and depends on the material from which the wheel/track is made and the condition of the pipe surface. Excessive pressing forces can unnecessarily dissipate power and block the robot inside the pipe, and insufficient forces can cause the robot to fall. Therefore, the adapting mechanism must maintain enough pressure against the wall to ensure sufficient traction force and avoid slippage. Those mechanisms should also minimize the variation of the traction force if the diameter of the pipe changes. To achieve those goals, passive mechanisms rely on the force generated by a spring. The active ones instead use actuation systems with DC motors and in some cases, sensors that can detect changes in the pressing force. All this can be integrated into a control loop, which gives more flexibility to the adapting mechanism.

All presented mechanisms are equipped with three sets of drive wheels or tracks evenly distributed at 120° around the central axis. Exceptions are the adapting mechanisms based on the pantograph linkage, which have the wheel sets located in the same plane.

3.1. Adapting Mechanisms Based on Slider-Crank Linkage

The slider-crank linkage shown in Figure 1, can be the most straightforward constructive solution for the adapting mechanisms. As mentioned above, robots may have several rows of wheels/tracks arranged radially around the axis. In this case, a slider-crank linkage will be required for each of them.

Yin et al. in [32] proposed a pipe robot that is designed for internal weld seam processing of thick wall pipelines. The robot can move in pipes whose inner diameter has a range from 270 mm to 380 mm and according to the authors has a good ability to pass through bent and inclined pipes. It consists of several modules that include a mobile unit, a detection unit and a grinding unit. The main function of the mobile unit is to provide the traction needed to pull the entire robot through the pipe. Figure 4 shows the schematic diagram of the adapting mechanism for one of the three drive wheels.

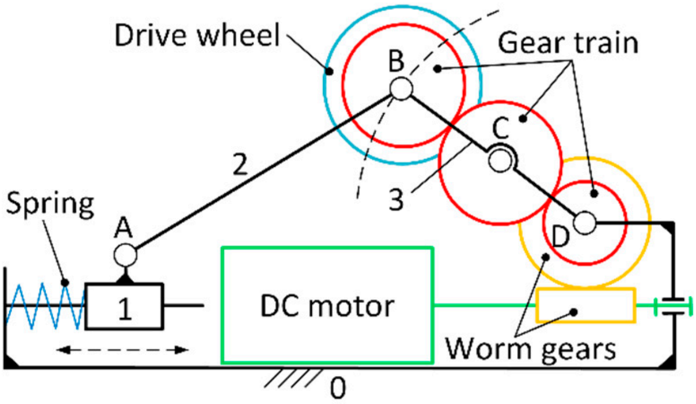


Figure 4. Schematic diagram of the adapting mechanism.

A single DC motor provides power to all three drive wheels through a worm gear and some gear trains. One of the elements of the adapting mechanism acts as a support for the robot's gear train. The pressing force against the pipe wall is provided by a spring acting on the slider *1*. Thus, by the expansion and contraction of the slider-crank linkage under the action of the force exerted by the spring, the adaptation of the robot to different diameters of the pipe is ensured. The variation of friction force between the wheels and the pipe wall is compensated by the force of the spring. The mathematical model that describes the relationship between the maximum traction force of the mobile unit, the size of the linkage elements and the spring force is presented in [32].

Min et al. in [33] and Aldulaimi et al. in [34] present a wheeled pipe inspection robot designed to move in pipes with multiple elbows and an inclination of max. 35°, with a diameter of 300 to 500 mm. The robot consists of two modules, one active and one passive. In both modules, each drive wheel is driven by its own gearmotor. The modules are connected with a universal joint to give the robot more flexibility. Figure 5 shows the schematic diagram of the adapting mechanism for the passive module.

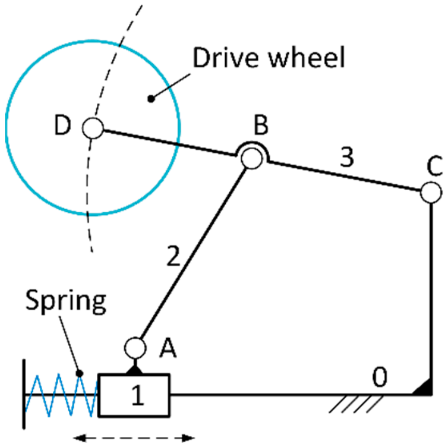


Figure 5. The adapting mechanism for passive module.

The only difference between the active and passive modules is the method in which the pressure force is obtained. In the active module, the slider *1* is moved by means of a screw driven by a motor and for the passive one by means of a spring. The slider's linear displacement determines the rotation of element *3* and also of the drive wheel, around the joint *C*. Although the robot has an active adapting mechanism, the pressure on the pipe wall cannot be controlled. The active module, by means of a fuzzy controller, allows only the adaptation to predetermined pipe diameters [34].

A self-adaptive pipe inspection robot with a multi-axis differential system and an active adapting mechanism is proposed by Zheng et al. in [35]. The total length of the inspection robot is approx. 370 mm and was designed to move in horizontal multi-bend pipes. The robot consists mainly of an adaptation/propulsion unit and a three-axis differential drive mechanism used to prevent the drive wheels from slipping. After the differential output, a bevel gear and a transmission chain are used to provide the necessary torque to the drive wheel. Figure 6 presents the schematic diagram of the adapting mechanism.

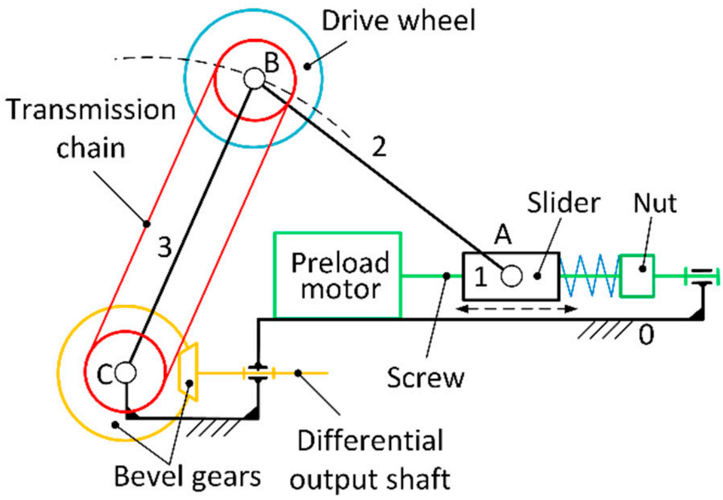


Figure 6. Mechanism for a self-adaptive pipe inspection robot.

The lengths of elements *2* and *3* are 130 mm and 120 mm, respectively. Slider *1* is moved by the lead screw's nut by means of a spring. A control system compares the pressure between the drive wheel and the inner wall of the pipe, which is measured indirectly by a force sensor mounted in the nut, with the required pressure value. Then, by means of the nut and spring, the preload motor transfers the necessary force to the adapting mechanism. The spring between the nut and slider ensures the ability to mitigate the impact with small obstacles inside the pipe. Thus, adjusting the position of the slider, pipes with a diameter between 330 and 372 mm can be inspected. The mathematical model for the relationship between traction force, mechanism geometry and the spring force through the slider to element *2* is available in [35].

Another inspection robot with a multiaxial differential gear is presented by Yang et al. in [36]. The proposed robot has an active adapting mechanism and three pairs of wheel sets, one active and the other passive. A multiaxial differential gear receives power from a single drive motor and distributes it to each active wheel via a bevel gear and the gear train. The schematic diagram of the robot's adapting mechanism is presented in Figure 7.

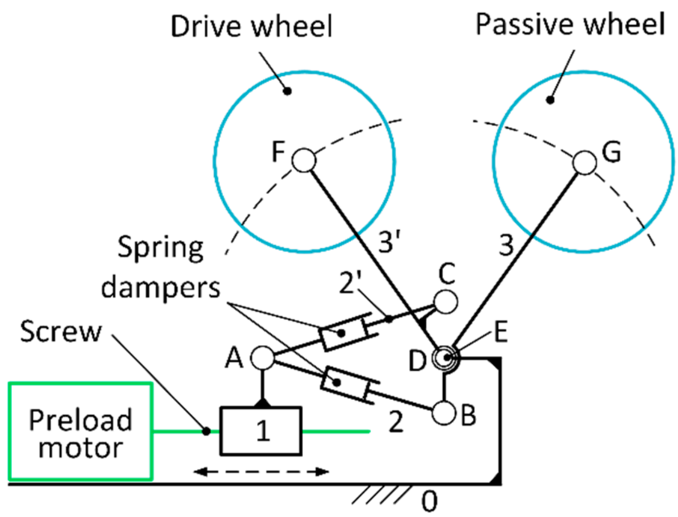


Figure 7. Adapting mechanism with dampers.

A screw driven by the preload motor moves the nut *1* back and forth. This movement causes the elements *3* and *3′* that support the wheels to rotate around the joints *D* and *E* thus, the robot is adapted to pipes with diameters between 130 and 180 mm. Even though the robot has an active adapting mechanism, the pressure against the pipe wall cannot be controlled. As each wheel arm has its own spring damper, the wheels can maintain the required wall pressing force. Additionally, each wheel can individually withstand small obstacles. The authors of the cited work performed several experiments that proved the robot's ability to move through horizontal and vertical pipes with elbows and different diameters.

Another application of the slider-crank linkage is in the support and/or self-centering units. Ren et al. in [37] use a slider-crank linkage to a support unit for a self-balancing robot with a helical drive. In this case, the linkage is similar to the one shown in Figure 1b with the mention that the supporting wheel is mounted at joint *B*, and the necessary force is provided by a spring on slider *1*. The support unit contains four radially arranged linkages and is designed to prevent the robot from rotating and to provide an anchor point so that the robot can center itself inside the pipe.

In the examples presented above, the adapting mechanism has 1DOF, being driven by a single actuator or spring. This causes all sets of wheels to move simultaneously. Additional mobility due to the presence of suspensions cannot be controlled. However, there are inspection robots that use, in the structure of the adapting mechanism, two independently driven slider-crank linkages which lead to 2DOF. This gives the robot greater flexibility in adapting to different pipe diameters and also allows the use of track-based locomotion systems.

Such an approach is presented by Tatar et al. in [11]. The proposed robot has a passive adapting mechanism and three pairs of wheel sets. Each set of three wheels can be moved separately by means of slider-crank linkages. The drive wheels receive the required power from a single motor through a combination of cylindrical and worm gears. The prototype of the inspection robot is shown in Figure 3a and the schematic diagram of the adapting mechanism and the drive system is presented in Figure 8.

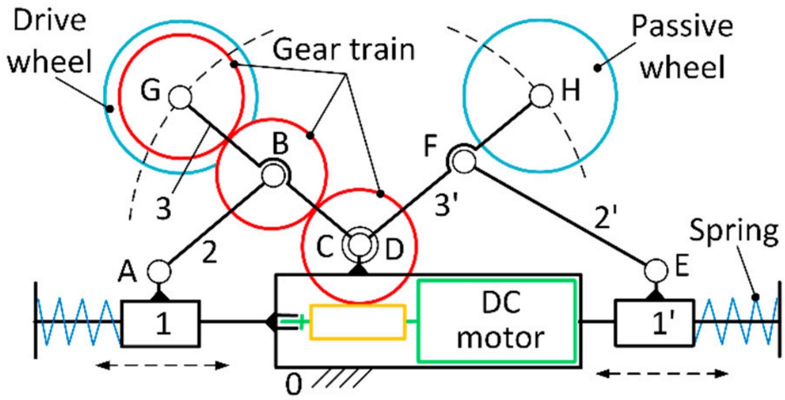


Figure 8. Adapting mechanism with 2DOF.

The lengths of elements *2* and *2′* are 53 mm and 95 mm while elements *3* and *3′* have a length of 58 mm. The robot has a total length of about 300 mm and was designed to move in pipes with a diameter between 140 and 190 mm. The variation of the friction force between the wheels and the pipe wall is compensated only by the force generated by the two springs. Since only one drive motor is used, the speeds of the drive wheels cannot be controlled independently. This makes it difficult for the robot to move through curved pipes. However, the experiments performed by the authors confirm that the robot can easily move through straight or slightly inclined pipes and can easily overcome small obstacles.

An inspection robot with independent underactuated parallelogram crawler modules is presented by Kakogawa et al. in [38]. The proposed robot has a passive adapting mechanism and three crawler modules. To accommodate variations in pipe diameter, each crawler module in the robot's structure is connected to a central unit via two identical slider-crank linkages as shown in Figure 9. The connection with the linkages is ensured through joints *G* and *H*. As the adapting mechanism has 2 DOF, these joints can change their relative position which allows the crawler module to be tilted if necessary. The axial length of the robot is 235 mm and the diameters of the pipes that can be inspected vary between 136 and 226 mm.

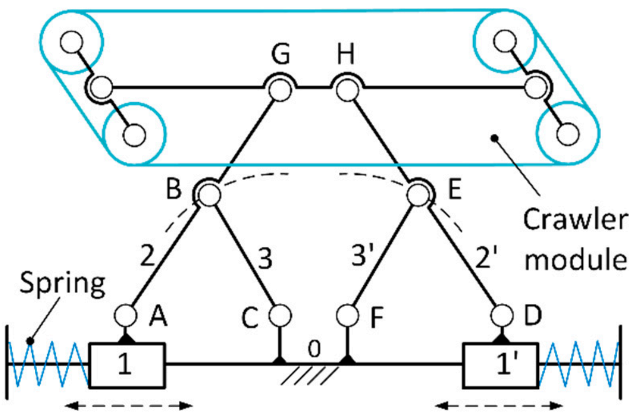


Figure 9. Adapting mechanism with crawler module.

Roh et al. in [39,40] present a passive adapting mechanism with three pairs of driving wheels that can move asymmetrically in the radial direction. The proposed adapting mechanism consists of two identical sets of slider-crank linkages at the front and rear of the robot. The follower arms of the slider-crank linkages are connected to each other through an element (part of a driving module) and joints *G* and *H* as shown in Figure 10.

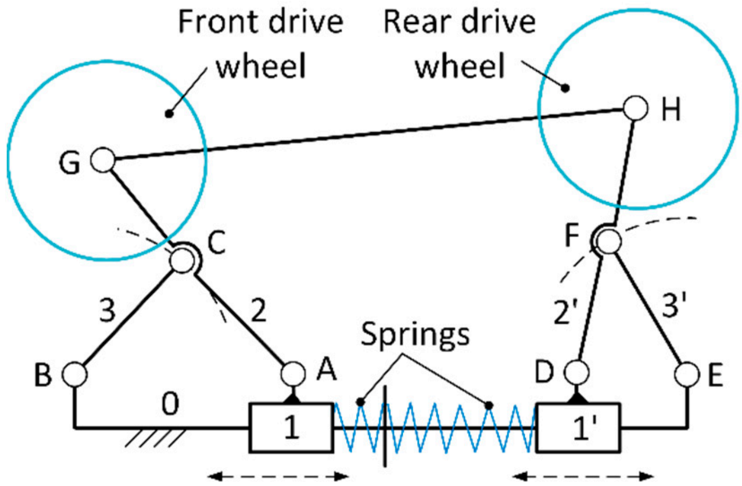


Figure 10. Adapting mechanism with inner springs.

The springs that preload the adapting mechanism are located inside which makes the robot have a compact structure and a total length of 150 mm. The proposed mechanism has been designed so that the wheels have good contact with the inside of the pipes and also to cope with the uncertain conditions inside the pipes. Thus, pipes with diameters between 85 and 109 mm can be inspected. Adaptation to different diameters and therefore the compensation of the friction force variation is based only on the springs force. The authors claim that the proposed robot can navigate in almost all types of pipe configurations, regardless of its position in the pipe or the direction of movement.

A similar mechanism is used by Kim et al. in [41]. In this case, the robot uses four pairs of interconnected slider-crank linkages. Each pair of linkages is connected to a track-based locomotion system, driven by two DC motors. The speed of each track is independently controlled to provide the ability to turn through any spatial pipe configuration involving any pipe fittings. When a track encounters obstacles, it also has the ability to tilt to increase the contact surface with the pipe wall. The length of the robot is 148 mm, and the outer diameter can vary between 127 mm at maximum shrinkage and 157 mm in a normal state.

Another robot with a track-based locomotion system that uses the same type of adapting mechanisms is proposed by Kwon et al. in [42]. The robot consists mainly of two identical modules interconnected by a compression spring and can inspect pipes with diameters ranging from 80 to 100 mm. The track-based modules allow the robot to maintain contact with the pipe surface during movement. As each track is independently controlled, it can steer at the elbows or T-branches of the pipes. The total length of the robot, including both modules and the compression spring is 230 mm.

3.2. Adapting Mechanisms Based on Pantograph Linkages

Pantographs usually have a larger stroke than other linkages with the same lengths of elements. A linear radial travel for the drive wheels can also be provided, which can be an advantage when the robot passes through the uneven surfaces of the pipes. Okada et al. in [43] propose one of the first inspection robots in this category. These types of robots, although they have a very simple structure, can face problems with stability and maintaining a stable position while moving through the pipes.

Tatar et al. in [44] propose an inspection robot whose three wheels are placed in the marginal joints of a planar pantograph linkage. In this case, the adapting mechanism actually represents the entire mechanical structure of the robot. A single drive wheel receives the required torque from a DC motor via a gear train. The prototype of the inspection robot is shown in Figure 3d, and the schematic diagram of the adapting mechanism is presented in Figure 11.

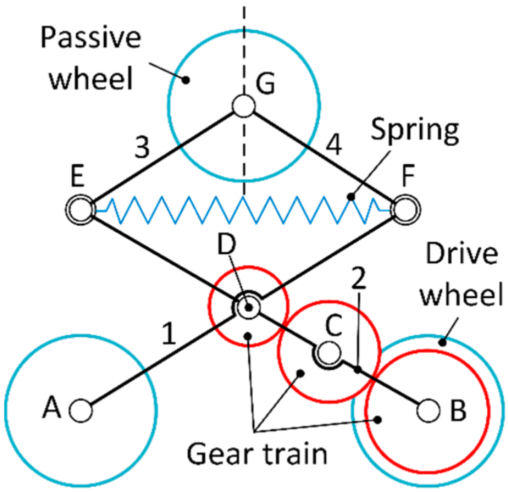


Figure 11. Inspection robot with pantograph linkage.

The force produced by a spring determines the rotation of elements *1* and *2* around the joint D. This causes the expansion of the mechanism and therefore the increase of the wall pressing force. The lengths of elements *2* and *3* are 50 and 25 mm, respectively, the robot being able to inspect horizontal or vertical pipes with diameters between 50 and 70 mm. By using wider wheels, it was possible to increase the friction force and thus avoid slipping. As all wheels are in the same plane, the robot is not able to maintain its orientation toward the inner walls of the pipe. The equation for determining the pressing force is available in [44].

Oya et al. in [45] present the development of a steerable in-pipe robot. The robot consists of two frames and a pantograph linkage that connects the centers of the two frames. The frames are identical, the wheels are independently steered, but the drive power is given only to the front wheels. Since the lower frame can rotate around the vertical axis, both frames can twist. This ability is useful for turning the robot around and avoiding obstacles. The proposed robot is able to move in three different ways: a straight line in which the wheel frames are parallel; a spiral movement in which the frames twist with a constant angle without steering and a steering movement in which all wheels are actively steered. Thus, the robot can avoid obstacles, and enter the joint spaces of L- and T-shaped pipes. The length of the robot is about 200 mm and the height is adjustable from 140 to 210 mm. Figure 12 shows the schematic diagram of the adapting mechanism for this robot.

There is a helical spring between joints C and D. Its force causes the pantograph to expand and the wheels of the two frames to be pressed against the inside wall of the pipe.

Park et al. in [46,47] propose a track-based inspection robot that moves through horizontal, vertical, and curved pipes with various diameters. Each of the three-track modules is connected to a pantograph linkage through a revolute joint so that it can rotate freely. This and the presence of two spring dampers helps the tracks to have improved contact with the uneven surface of the pipe. Figure 13 presents the structure of the active adapting mechanism.

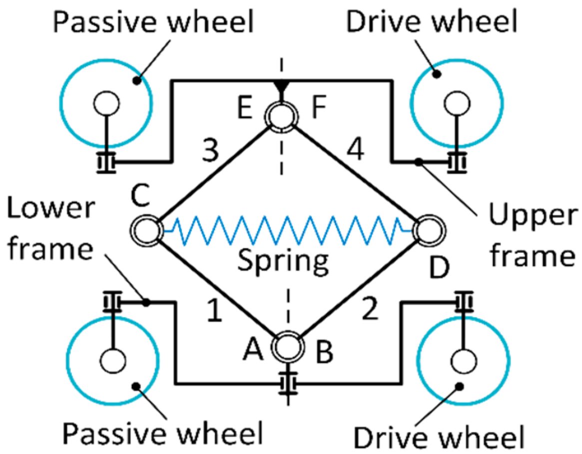


Figure 12. Inspection robot with steering wheels.

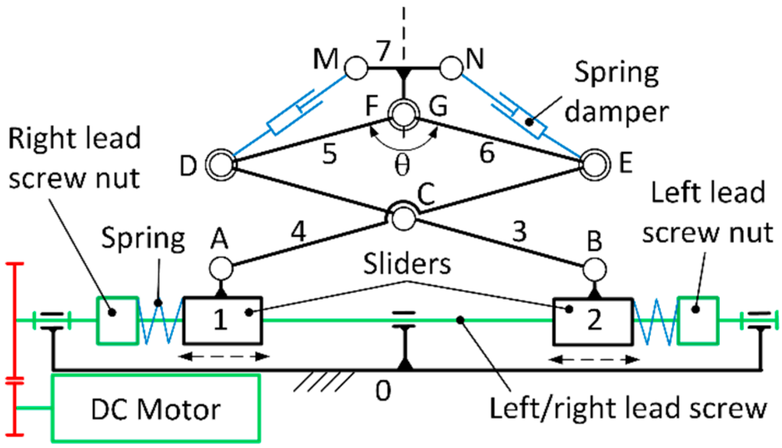


Figure 13. Active adapting mechanism based on a pantograph linkage with two sliders.

A gear train transfers the power of a DC motor to three screws so that they can rotate synchronously and ensure the movement of the pantograph linkages. The pantograph sliders *1* and *2* are moved with a left/right threaded screw and are pushed by the nuts by means of two springs. These springs give the adapting mechanism a certain compliance with the movement in the radial direction. The robot estimates the pressing force by observing the relationship between the forces acting on the pantograph and the movement of the two sliders. The slider displacement is calculated using the DC motor encoder counting value and the measured value of angle θ. A mathematical model for the relationship between wall pressing force and mechanism geometry is available in [46]. The total length of the robot is 390 mm and the radial size can vary between 400 and 700 mm. Although the robot is adaptable to changes in diameter and pipe inclination, it may experience problems with loss of contact when changes of direction are required in a branched pipe.

An interesting constructive solution is proposed by Choi et al. in [48]. The inspection robot consists of three modules which are a front and a rear driving vehicle and one control module. Each driving vehicle has two independent modules connected by an active double universal joint that offers omnidirectional steering capability. As the adaptive mechanism should be as simple as possible, it uses a pantograph linkage with one slider that allows natural folding and unfolding. The proposed adapting mechanism is shown in Figure 14.

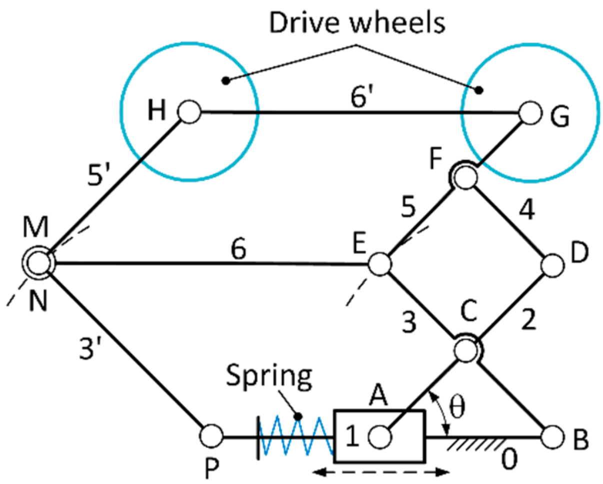


Figure 14. Adapting mechanism based on pantograph linkage with one slider.

The wall pressing forces are obtained by means of a spring that acts on slider *1* of the pantograph linkage. When the proposed mechanism contracts or expands the wheels are pressed only along the radial direction. The relationship between the pressing force, the spring constant and its initial length is available in [48]. This relation is determined considering the length of the element *5* and the measured value of the angle θ. Thus, forces can be easily preset according to the payload, by adjusting the spring constant and the initial deformation.

3.3. Adapting Mechanisms Based on Combined Linkages

These adapting mechanisms are obtained starting from the four-bar linkage as a basic unit to which a slider-crank linkage is added. As in the examples presented above, in this case, the mechanism can also be operated passively by means of springs or actively by means of actuators.

Jiang et al. in [49] propose a three-axis differential drive pipe robot, which consists of a differential mechanism and a mechanism for adapting to variations in pipe diameter. The robot is equipped with three pairs of drive wheels. A 3-DOF tri-axial differential drive mechanism for steering allows the robot to easily adapt to any existing pipe configuration. After the differential output, a bevel gear and a set of synchronous belts are used to provide the required torque to the driving wheels. Figure 15 shows the schematic diagram of the adapting mechanism.

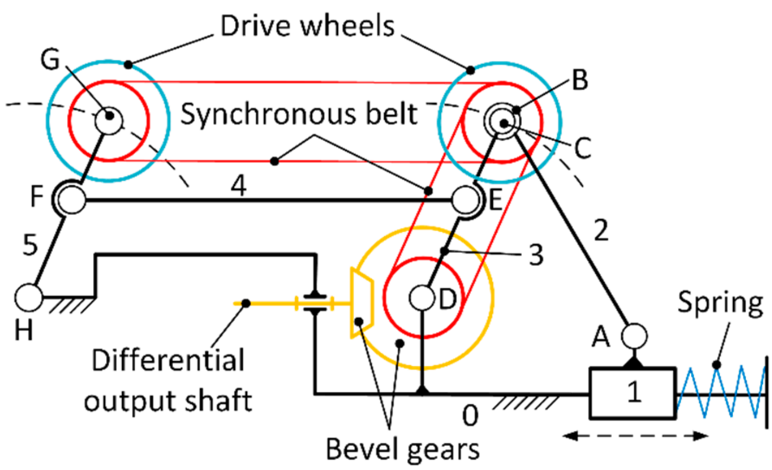


Figure 15. Adapting mechanism based on combined linkages.

The force required to adapt the robot to the inside diameter of the pipe is applied in the axial direction by means of a spring at which the pre-tightening can be adjusted. The movement of slider *1* causes the rotation of elements *3* and *5* together with the drive wheels around the joints *D* and *H*. This ensures sufficient pressure on the pipe wall so that the diameters covered by the robot can vary from 275 to 300 mm.

Tatar et al. in [50,51] propose two inspection robots that use similar adapting mechanisms. In both cases, the robots have three identical adapting mechanisms with two pairs of wheels. The required force is generated by a helical spring also placed on the central axis. To drive the wheels, the first proposed robot uses a single DC motor and a combination of worm and cylindrical gears. One of the elements of the adapting mechanism also acts as a support for the robot's gear train. The first prototype of the inspection robot is shown in Figure 3b, and the schematic diagram of the adapting mechanism is presented in Figure 16.

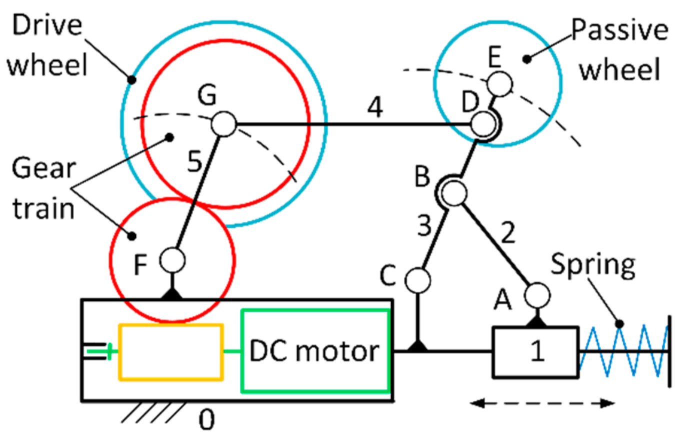


Figure 16. Passive adapting mechanism.

The total length of the robot is 140 mm and the pipe diameters that can be inspected are between 100 and 125 mm. The second prototype is shown in Figure 3c and has a gear motor for each drive wheel. It can inspect pipes with diameters between 140 and 200 mm and has a length of 280 mm. Both prototypes have good mobility and also the ability to overcome small obstacles when moving through horizontal or inclined pipes. The second prototype, because it has independently driven drive wheels, can easily move through bend pipes.

Chang et al. in [52] propose a novel pipeline inspection robot with a belt-driven ridged cone-shaped set of wheels. The three belt-driven wheels are connected to the main body through adapting mechanisms based on combined linkages. Figure 17 presents the schematic diagram of the proposed mechanism.

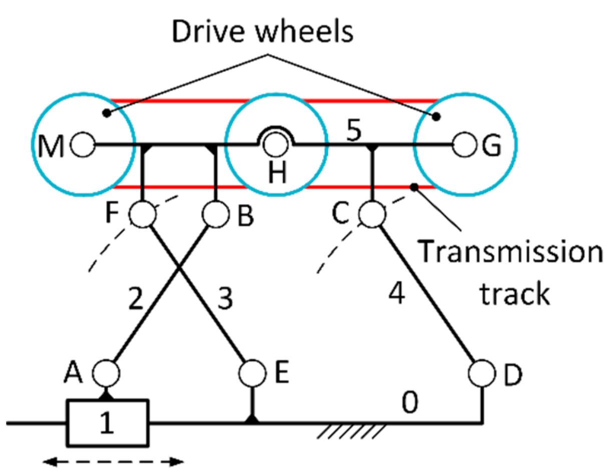


Figure 17. Adapting mechanism with belt-driven wheels.

Each of the three adapting mechanisms contains an electric linear actuator for the longitudinal movement of slider *1*. The active adapting mechanism does not allow the control of wall pressing force, but the mathematical model that describes the relationship between this force, the geometry of the mechanism and the force developed by the linear actuator is presented in [52]. To ensure sufficient frictional force and to overcome small obstacles the robot relies on wheel design. As the mechanisms can be operated individually the robot can easily adapt to variations in diameters or rough/irregular surfaces in the pipeline. As each wheel set is operated and controlled independently, the proposed inspection robot can pass through elbows and T-branches. The length of the robot is approx. 460 mm, and its outer diameter can be changed from 300 mm to 390 mm.

A robot with a track-based locomotion system that uses the same type of adapting mechanism is proposed by Ou et al. in [53]. The sliders of the adapting mechanisms are moved simultaneously by means of a screw driven by a DC motor. Controlling each track module independently, the robot is able to move through elbows and Y- or T-branches. The length of the proposed robot is approx. 410 mm, and the adaptation mechanism makes it possible to move through pipes with a diameter between 300 and 450 mm.

Ling et al. in [54] propose a design method for an intelligent pipe inspection robot with the ability to adjust its diameter to fit different pipes. As in the previous examples, the inspection robot consists mainly of three track-based modules connected to the robot body through combined linkages. As a novelty, the authors introduced a spring damper in the structure of the adapting mechanism. A certain degree of flexibility of the mechanism would make it possible for the robot to adapt more easily to small variations in pipe diameter, surface unevenness due to welded seam or corroded pits.

Zhang et al. in [55] present the design and stability analysis of a crawler-type inspection robot with radial adjustment ability. The adapting mechanism can realize the active adjustment of the outer diameter of the robot so that the track modules can be in contact with the pipe wall as much as possible. Each track is driven independently, thus the robot can move in the pipe through so-called three-shaft differential driving. Figure 18 shows the schematic diagram of the active adapting mechanism.

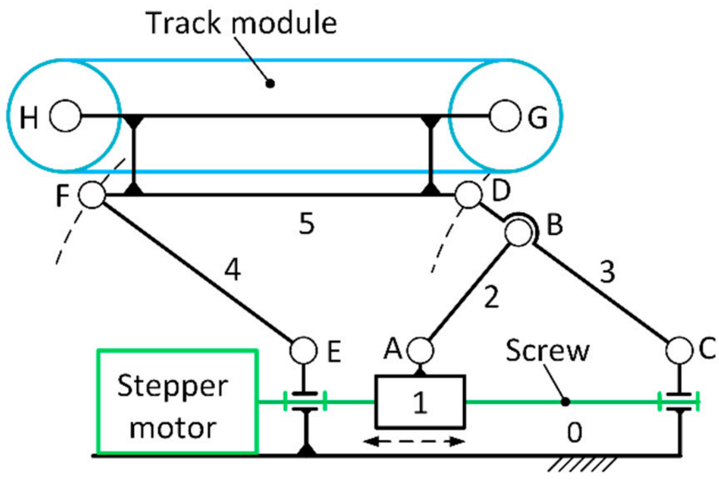


Figure 18. Active adapting mechanism with track module.

The robot is adapted to different diameters by moving slider *1* by means of a ball screw driven by a stepper motor. The adapting mechanism is equipped with a force sensor for active control of the wall pressing force. The mathematical model that describes the relationship between the pressing force, the geometry of the mechanism and the torque developed by the stepper motor is presented in [55]. The total length of the robot is 380 mm, and it can inspect straight curved or inclined pipes with a diameter between 220 and 320 mm.

4. Discussion

The robot's adapting mechanisms must ensure a possibility of pushing against the pipe wall with adequate pressing forces. Furthermore, the pressing forces must not have significant changes during navigation, in order to provide stable traction and flexible locomotion. Last but not least, the mechanism should be simple and small in size, to take up as little space as possible inside the pipes and not significantly increase the mass of the robot [48]. The specifications for the inspection robots presented in this paper and for their adapting mechanisms are summarized in Table 1.

Table 1. Comparison between the adapting mechanisms of the robots presented in the paper.

Ref. No.	Authors	Type of Linkage	Adapting Mechanism Type	Robot Length (mm)	Locomotion Type	Traction Force (N)	Diameter Range (mm)	Pipe Geometry		
								Max Slope (°)	Branch	Elbow (°)
[32]	Yin et al.	Slider-crank (1DOF)	Passive	Unk.	Wheel	341.4	270–380	20	No	Unk.
[33]	Min et al.		Active&Passive (2 modules)	685	Wheel	Unk.	300–500	35	No	Unk.
[34]	Aldulaimi et al.									
[35]	Zheng et al.		Active	370	Wheel	Unk.	330–372	Unk.	No	Unk.
[36]	Yang et al.		Active	128	Wheel	Unk.	130–180	Unk.	No	Unk.
[11]	Tatar et al.	Independently driven slider-crank (2DOF)	Passive	300	Wheel	10.4	140–190	90	No	45
[38]	Kakogawa et al.		Passive	235	Track	Unk.	136–226	30	No	Unk.
[39,40]	Roh et al.		Passive	150	Wheel	9.8	85–109	90	T	90
[41]	Kim et al.		Passive	148	Track	Unk.	127–157	90	Y and T	45; 90
[42]	Kwon et al.		Passive	230	Track	Unk.	80–100	90	T	90
[44]	Tatar et al.	Pantograph	Passive	Unk.	Wheel	Unk.	50–70	Unk.	No	Unk.
[45]	Oya et al.		Passive	200	Wheel	8.1	140–210	90	T	90
[46,47]	Park et al.		Active	390	Track	Unk.	400–700	90	T	90
[48]	Choi et al.		Passive	Unk.	Wheel	Unk.	Unk.	90	T	90
[49]	Jiang et al.	Combined (Four-bar and slider-crank linkages)	Passive	550	Wheel	450	275–300	90	No	90
[50]	Tatar et al.		Passive	140	Wheel	3	100–125	90	No	90
[51]			Passive	280	Wheel	18.5	140–200	Unk.	No	45
[52]	Chang et al.		Active	460	Wheel	Unk.	300–390	Unk.	T	90
[53]	Ou et al.		Active	410	Track	Unk.	300–450	30	Y and T	Unk.
[55]	Zhang et al.		Active	380	Track	Unk.	220–320	Unk.	No	90

Table 2 shows a comparison between the linkages used in the adapting mechanisms presented in the paper. Slider-crank-based adapting mechanisms have a simple design and construction and ensure good maneuverability for the robot. Multiple modules will add the advantage of having greater stability and traction and the ability to carry inspection tools. The main disadvantage is the slippage when moving vertically.

Inspection robots whose adapting mechanisms are based on independently driven slider-crank linkages or combined linkages, generally have greater structural complexity. However, they can travel along reducers, elbows and also steer in the branches by using various steering systems. For wheeled robots, the most used is the three-axis differential, which performs steering by modulating the speed of the drive wheels. The steerability for track-based robots is achieved by using differential speed on each track.

Table 2. Comparison between the linkages used in the adapting mechanisms.

Type of Linkage	Slider-Crank (1 DOF)	Independently Driven Slider-Crank (2DOF)	Pantograph	Combined (Four-Bar and Slider-Crank Linkages)
Suitability	Wheel based robots	Wheel/track-based robots	Wheel/track-based robots	Wheel/track-based robots
	Horizontal pipes	Horizontal/vertical pipes	Horizontal/vertical pipes	Horizontal/vertical pipes
	Slightly inclined pipes	Elbows Y- and/or T-branches	Elbows T-branches	Elbows Y- and/or T-branches
Advantages	Simple construction	Simple construction	Larger stroke	Active/passive adapting mechanism
	Active/passive adapting mechanism	Ensures a higher applied pressure on the pipe wall	Active/passive adapting mechanism	Ensures a higher applied pressure on the pipe wall
	Three-axis differential drive	Three-axis differential drive		Three-axis differential drive
	Lighter and smaller in size	Small size		
Disadvantages	At least two interconnected modules are needed to ensure stability	More complicated mechanical structure	Stability issues	More complicated mechanical structure
	The wheels may get stuck in the holes inside the pipe	Passive adapting mechanism	Larger radial dimension	Larger axial dimension

One of the main advantages of pantograph-based adapting mechanisms is a larger stroke. This can be useful for inspecting pipes with large diameter variations. A linear radial travel for the drive wheels/tracks can be an advantage when the robot passes through the uneven surfaces of the pipes. The wheeled versions of these robots, although they have a simple structure, have problems maintaining a constant orientation along the pipe.

Based on the trends in the research of in-pipe inspection robots, two approaches can be distinguished: the researchers' approach, which is mainly focused on design and identifying the behavior of the robot inside the pipe in ideal situations, and the industry approach, which is focused on aspects that are encountered in real situations [56]. The wall pressed inspection robots show good maneuverability and can easily adapt to irregular pipes, but the relatively low ability to overcome obstacles limits their application in the industrial environment. Despite their constructive simplicity, passive adaptation mechanisms have proven to be less effective if robots have to deal with large variations in pipe diameter. Such mechanisms may have difficulty maintaining sufficient pressure when moving through vertical pipes.

Future developments should identify new active systems, with a simple mechanical structure, to overcome this drawback. To ensure greater flexibility and adaptability, control algorithms that use signals from force sensors should be integrated.

5. Conclusions

In-pipe inspection robots are a category of robots that have been extensively studied and for which many interesting solutions have been proposed and used. For many categories of inspection robots, the linkages used in the adapting mechanisms determine how they operate and their performance. Thus, the present paper aims to provide an overview of the most commonly used adapting mechanisms for wall pressed type inspection robots. It should be mentioned that only those linkages that appear more frequently in the structure of inspection robots were presented. This work can provide an updated reference for researchers in the field of inspection robots, regarding the main types of adapting mechanisms.

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