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Procedia Engineering 41 (2012) 1456 – 1462

Engineering Procedia

www.elsevier.com/locate/procedia

2012 International Symposium on Robotics and Intelligent Sensors

A Review: Hybrid Locomotion of In-pipe Inspection Robot

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Abstract

In the past five years, researchers have improvised the existing in-pipe inspection robots by developing hybrid locomotion by combining two or more propulsion mechanism in achieving robust but yet flexible robot platform. In this paper, several hybrid robots have been reviewed and categorized according to their implemented locomotion system. The hybrid locomotion systems are caterpillar wall-pressed type, wheeled wall-pressed type and wheeled wall-pressing screw type. Each hybrid locomotion system is developed according to distinct design requirements for specific environment and might be not suitable for other application. The aim of this review is to highlight the current innovation of in-pipe robot for inspection. Based on the study, wall pressed type is the most popular main locomotion system in in-pipe robot development. Most of the prototypes are able to travel into branches with the same diameter as the pipe. Integration of caterpillar wheel gives more advantage in preventing motion singularity problem while surpassing branches. On the other hand, wheeled wall-pressed type provides advantage in high speed mobility. Wheeled wall pressing screw type gives the best navigation in curved pipe. None of these inventions show their ability in navigating bigger pipe to smaller branches.

Keywords: Hybrid locomotion; in-pipe inspection robot; wall-pressed robot

1. Introduction

In-pipe inspection robots are widely utilized in oil and gas industry, power plant industry and sewage system. These robots are applied to inspect defects, cracks and internal erosion which is due to many reasons such as degradation, creep, overheating, corrosion and others. Numerous in-pipe inspection robots have been built for the last two decades based on wheeled type, caterpillar type, snake type, legged type, inchworm type, screw type and PIG type. Each of the robots is developed according to distinct design requirements for specific environment and might be not suitable for other application. Therefore, by single locomotion system the inspection robot platform is only applicable for certain pipe configuration. Recently, combination of two or more locomotion system has been implemented to pipe inspection robot for more advantages in term of robustness and flexibility to their inventions. By using hybrid locomotion system, the inspection robot is able to adapt and navigate in a various pipe configuration.

Each of single locomotion system offers few advantages albeit certain degree of limitation in term of various working condition adaptability. Wheeled type is widely used especially with differential driving due to its ability in branches navigation [1]. Caterpillar type has advantages of travelling on uneven surface and overcoming obstacles in the pipe [2]. Snake and legged type are usually designed for high mobility and branches pipes [3]-[6]. Inchworm type robots have an advantage of moving in curved pipes [7], [8]. Screw type is usually has simple structure and easy to control [9].

1877-7058 © 2012 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2012.07.335

For the past five years, many hybrid locomotion systems have been introduced to inspection robot and can be characterized under three categories; caterpillar wall-pressed type, wheeled wall-pressed type and wheeled wall-pressing screw type as shown in Fig. 1. A brief explanation of each hybrid type is discussed in Section II. In Section III, all the hybrid types mentioned in Section II are reviewed by comparing their mechanism as well as working performance. The finding and review is concluded in Section IV.

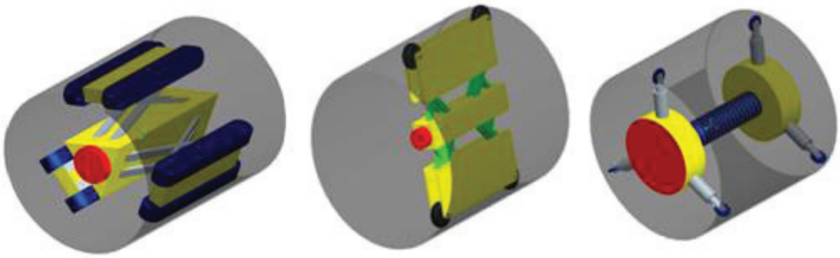

Fig.1. (a) Caterpillar wall-pressed type; (b) Wheeled wall-pressed type; (c) Wheeled wall pressing screw type

2. Hybrid Locomotion

Single propulsion mechanism is wheeled type, caterpillar type snake type, legged type, inchworm type, screw type and PIG type. Each of the locomotion exhibits their own advantages and limitation depends on in-pipe working condition. With the intention to overcome the drawback of each single propulsion mechanism, assimilation of two or more locomotion system as new innovative drive system is considered uttermost important. The hybrid locomotion system solves limitation set propulsion mechanism as well as unique pipe condition such as variation of pipe diameter, curvature, inclination etc.

2.1. Caterpillar wall-pressed type

In order to support the robot structure, caterpillar track is pressed to the wall. Caterpillar wheels provide good traction force for the robot to move forward and backward. Combination of these two mechanisms allows the robot to adapt various pipelines diameter, travel smoothly on uneven surface and curvature. Generally, this type of robot consists of three main parts such as main body, caterpillar wheel and flexible linkage mechanism. Figure 2 shows the structure of the caterpillar wall-pressed type.

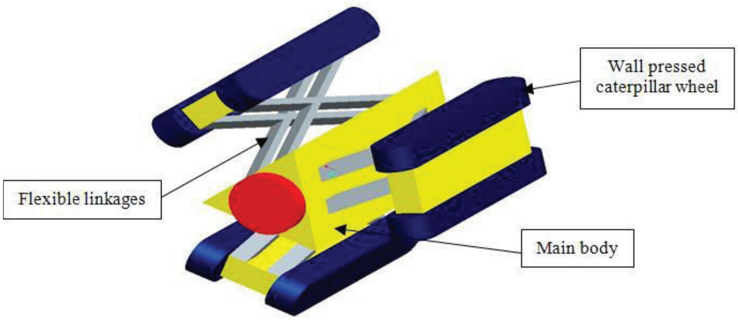

Fig.2. Caterpillar wall-pressed structure[11]

FAMPER [10] is designed to inspect 150 mm pipelines and consists of four caterpillar tracks with extendable link systems. Due to its flexibility, it can manoeuvre in damaged pipelines and pass over obstacles. Caterpillar track is attached to rectangular central body platform using four independent suspension links that can contract from 157 mm to 127 mm. Spring and flexible links act as a suspension system to provide sustainable performance in uncertain pipeline condition. Each caterpillar is controlled independently to ensure that the robot can navigate in pipe branches and elbows by differentiating their speeds. The prototype was tested in test bed of 45° and 90° elbow as well as T-branch with outstanding mobility performance. Normal wall pressed robot encounters motion singularity problem, of which some of the wheels lost their contact while turning. On the other hand, FAMPER is designed with exceptional mechanism for self-adjustability and overpass obstacle. The caterpillar wheels are designed to be 5° tilted with respect to the main body to provide self-adjust ability. This enables all caterpillar wheels to get in contact to the surface. Furthermore, a bendable segmented caterpillar mechanism is designed to enhance the flexibility in turning and crossing obstacles. The caterpillar mechanism is also equipped with shrinkable shaft to provide support for the caterpillar frame. This shaft helps the robot to reduce its length up to 50% and enable the robot to inspect pipelines in wider range.

Y. S. Kwon et al. [11] applied the same locomotion combination with slightly different arrangement. Three caterpillar wheels are arranged 120° apart and connected by a pair of four bar linkage mechanism each to the triangular main body. Linkage structure enables the caterpillar wheel to adapt pipe diameter change. The robot exterior diameter is 80 mm and can expand up to 100 mm. The advantage of caterpillar wheel in maintaining contact with the surface is further improved by utilizing silicon as outer wheel surface to enhance the gripping and propelling force. Each of the caterpillar wheels is controlled independently. The caterpillar wheels can also drive the robot in omni-direction. Two robot modules is proposed to avoid motion singularity which enable one of the caterpillar wheel to lose contact at turning position. Compression force stored in the spring attached between the modules enables the front module to pass the turning position by pushing it. On the other hand, rear module is pulled by expansion force stored in the spring. Due to its light weight design, the 532g weight robot can encounter transition from horizontal to vertical pathway. The prototype was successfully tested in an acrylic pipelines with multiple cast iron elbows and T-branches that is the same as pipeline type 80 used in Korea and Japan.

PAROYS-II [12] also implements the combination of caterpillar wheels and wall press locomotion. Caterpillar wheels are located 120° apart to the centre module. Each of the caterpillar wheels can be controlled independently. However, PAROYS-II uses leads screw in centre module to expand and retract its pantograph mechanism to adapt pipe diameter ranging from 400 mm to 700 mm. Another special feature is its caterpillar wheels consists of two segmented module, frontal and rear tracks. Frontal track is connected to a RC servomotor which is attached to the rear track. The ability of frontal track to rotate maintains the track in contact with uneven surface. Revolute joint that connects the track module and pantograph mechanism allows PAROYS-II to turn in curved pipe efficiently without any motion singularity issue. These two special features in PAROYS-II caterpillar wheels strengthen its ability to overcome obstacles.

K. Sato et al. [13] developed modular caterpillar wall pressed robot that consist of identical units and connecting links. The number of units needed is determined by the pathway condition and diameter of the pipe. For 300mm diameter pipe, three units are required to move straight. Two types of actuators are used for each unit movement. RC servomotor is used to rotate the links so that the unit is pushed against both side of the wall. DC motor is used to manoeuvre the unit forward and backward directions. The unique feature of this robot is its rotation mechanism. A force sensor is used to control the angle of the links. First, the units are rotated to be in vertical direction and pushed the upper and bottom wall. Then, the robot is rotated sideways of the wall for alignment of the robot movement direction and the joints. In order to move, the robot is changed to a movable mode where the units are arranged alternately to push the both side of the wall. The prototype is tested for straight movement and turning ability. On top of that, this robot is also able to move in vertical pipe by applying sufficient force between 5.0 N and 8.5 N.

2.2. Wheeled wall-pressed type

Wheeled type with differential drive system provides good steering ability especially for navigating pipe branches. Integrating this feature in a wall press robot enhance the performance of a common legged wall press type. This hybrid locomotion has no significant difference in term of propulsion mechanism in comparison with the previous type except the lower amount of traction force exerted by the wheels. However, this type of robot has its own significance in terms of simple structure for specific design requirements. Furthermore, wheels are more efficient to be used for high speed mobility compared to the caterpillar track. Figure 3 shows the structure of wheeled wall-pressed robot that consists of main body, wheel and flexible linkage mechanism.

Y.S. Kwon et al. [14] employed an advanced wheeled wall pressed pipe inspection robot with two wheel chain. Normal wall pressed robots require at least three wheel chains and occupy most of the central module area. Similar to other wall pressed robot, folding mechanism is employed to adapt the diameter change of the pipe. This robot is designed to inspect pipelines ranging from 80 to 100mm in diameter. The wheel chains are installed 180° apart supported with parallel folding mechanism to the main body and the wheels are in contact with the wall. With this new approach, more space is available to mount extra cameras on the other two sides of the body. The special feature of the robot is that it has screw motion ability to get closer and capture clearer image of the pipe by using the side camera. This operation is called detecting mode. This motion is attained by positioning the wheels in opposite direction. Turning ability can be achieved by controlling the same angle of wheel chains in the same direction of turning. These two motions give wheel type an advantage as compared to caterpillar wheel. Unlike the other wall pressed robot, this locomotion system requires less steering control because it only needs same speed to turn the robot in respective direction. The driving mode operation is where the robot moves in a straight movement and can be achieved if there is no steering angle. It has been proven by experiment that with one module, this new approach can overcome the motion singularity problem.

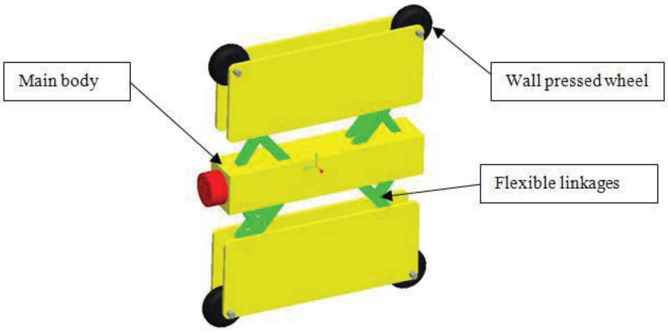

Fig. 3. Wheeled wall-pressed structure[14]

E. Dertien et al. [15] implemented the same locomotion system but with modular approach. The robot consists of seven modular that give specific functions; two driving modules, two clamping modules, two payload modules and a central rotation module. This mechanism is design to cater pipe inspection ranging from 63mm to 125mm in diameter. The unique feature of this robot is its capability to turn at a sharp mitered bend. Thus, the module exhibits a curved shape. Despite moves in vertical direction, this robot moves sideways of the pipe to avoid contaminants and dust on the bottom of the pipe. The bending modules keep the robot to be in the center plane of the pipe. The torque exerted by the bending modules is from the first two modules and the last two modules. They are equipped with motors and spring to give the ability to generate the clamping torque.

H. O. Lim et al. [16] proposed two modular wheeled wall-pressed robots. The fore leg system and rear leg system of the robot are connected by a body. Each system consists of three legs and is arranged 120° apart using worm gear system. The legs used linkage approach and the opening of the linkage can be controlled by RC servomotor. This allows the robot to adapt various pipelines diameter in the range of 125mm to 180 mm. Forward movement is achieved by pushing the legs to the pipe wall and rotated the wheel by a DC motor. A DC motor installed in the body provides twisting ability to the robot. Image of defects of the pipe is captured by a CCD camera installed in the front fore leg system.

2.3. Wheeled wall pressing screw type

Wheeled wall pressing screw type combined three locomotion systems in one robot. Wheel feature in the robot provides less friction force between the normal screw type and the pipe wall. Usually, screw type motion requires rotator and stator to produce the motion. Figure 4 shows the structure of this wheeled wall pressing screw type robot. The best feature about this type of robot is it requires at least one actuator to move.

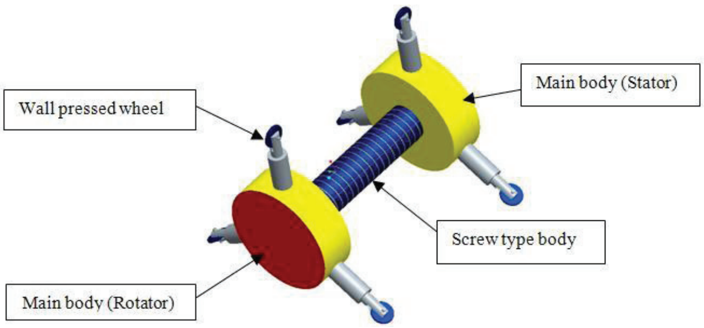

Fig. 4. Wheeled wall pressing screw structure[18]

Y. H. Zhang et al. [17] designed a flexible squirm type robot that interrogates these three locomotion system by using just one motor. The uniqueness of this robot is it can also be operated in online condition where the pressure caused by flowing fluid is used to drive the robot. This robot is equipped with magnetic wheel devices that can adapt the pipeline diameter change by controlling its leg or guide rod. Magnetic wheels help the robot to adhere to the iron wall and support the whole robot body. The brake installed in the leg provides electromagnetic force to the permanent magnet wheel. The ice cream cone shape of the robot also gives an advantage to it in turning position. It consists of two parts, ice cream scoop shape on the left and the cone or right body. The flexible helical axle and the gear nut in the ice cream scoop body perform a screw drive mechanism. To move in the pipe, left body has to be fixed on the wall while the helical axle pushed the right body. Reversing the motor direction can drive the left body to the right. A guide head is used to steer the robot. It is installed in the right body and consists of controlled rods that determine the turning angle. These controlled rods are connected to the left body. In L-type elbow, the guide head will follow the structure of the elbow to turn. The flexible helical axle bends to be parallel to the guide head rotation axis. In T-branches, the same procedures applied to the robot except that the controlled rods are pulled by the left body to angle itself in 45°.

A. Kakogawa et al. [18] implemented screw drive mechanism system in their advance wheeled wall pressing innovation to reduce the actuator used. This robot is invented to cater a straight and curved pipe. Therefore, it is sufficient to used screw type locomotion to transverse the curved pipe. Wheeled type is chosen due to its ability to move in high speed. Furthermore, it can decrease the frictional force on the wall exerted by the screw drive type with no wheels. Wall pressing method is the best locomotion system for climbing purposes as it can exert the normal force from the wall to counter the gravity force acted by the body.

3. Discussion

From the trend of in-pipe inspection robot development for the past five years, wall pressed type is the most popular type. It has been integrated with other types of locomotion to enhance its ability for certain conditions. Caterpillar wall-pressed and wheeled wall-pressed types are able to overcome the branches. However, caterpillar wall-pressed is better in surpassing branches with more contact surface at the wall. The linkage system integrated in most of the design also aided the robot to avoid motion singularity. Nevertheless, wheeled wall-pressed robot designed by Y.S. Kwon et al. has proved its advantage by performing screw motion. This type of motion is very useful in capturing closer image of the pipe using side camera. The third hybrid system shows its best ability in navigating curved pipe. Most of these robots are able to inspect pipelines and branches of the same diameter. However, none of these are tested in different size of pipe and branches at the same time. For wall pressed type, it is easy to expand its diameter from small pipe to bigger pipe, but it is a bit difficult to do the other way around. The robot may get stuck at the entry of smaller pipe. The major problem occurred if the difference in diameter is really big such as 300mm diameter of main pipe to 80mm diameter of branches. The suitability, advantages and disadvantages of the hybrid locomotion in-pipe robot are summarized in Table 1. Table 2 shows the detailed comparison performance for each type of robots discussed earlier.

4. Conclusion

From the past two decades, many type of single locomotion system have been invented and tested. However, as the technology changes, these type of locomotion provide some limitations for current situations. This review paper discusses on the current development of in-pipe robot. Researchers have hybridized the common type of in-pipe robot locomotion systems for a better performance. The results achieved by the experiments show that by employing hybrid system, most of the robot can overcome motion singularity problem especially when navigating branches and curved pipelines. Besides that, the hybrid system manages to increase the flexibility of the robot in terms of manoeuvring and image capturing ability. With hybrid type, it is possible to design a robot with multiple types of motion. However, none of these prototypes have been assessed in the pipe with the sudden change diameter with branches.

Acknowledgements

The authors wish to thank Ministry of Higher Education Malaysia through ERGS grant (ERGS/1/2011/TK/UNITEN/02/11).

Table 1: Comparison on hybrid in-pipe robots

Type	Caterpillar wall-pressed	Wheeled wall-pressed	Wheeled wall pressing screw
Suitability	Pipe with same diameter branches Curved pipe Horizontal pipe Vertical pipe	Pipe with same diameter branches. Curved pipe. Horizontal pipe Vertical pipe	Pipe with same diameter branches. Curved pipe. Horizontal pipe Vertical pipe
Advantages	Can adapt various pipe diameters. Able to provide omni-directional motion. Large contact area with the wall. High traction force. Able to conquer uneven surface. Able to climb	Can adapt various pipe diameters. Able to provide screw type motion. Less friction force. High speed mobility. Able to climb	Can adapt various pipe diameters. Require small radius of curvature to turn. Minimal actuator. Lighter and smaller in size. Able to climb.
Disadvantages	High friction force. No evidence in navigating from bigger to smaller size pipe.	Require bigger radius of curvature to turn. Less efficient on uneven surface. No evidence in navigating from bigger to smaller size pipe.	No evidence in navigating from bigger to smaller size pipe.

Table 2: Performance table

Performances		Caterpillar wall-pressed	Wheeled wall-pressed	Wheeled wall pressing screw
Pipe configuration	Horizontal	√√√	√√√	√√√
	Vertical	√√√	√√√	√√√
	T- joint	√√√	√√	×
	L- joint	√√√	√√√	√√√
Curving	45°	√√	√√	√√√
Variable pipe diameter		√√√	√√√	√√
Sudden change pipe diameter	Small pipe to bigger branch	√√√	√√√	√
	Big pipe to smaller branch	××	××	××
Structure	Simple	×	√√	√√
	Light	×	√	√√
Surface condition	Smooth	√√√	√√√	√√√
	Uneven	√√√	×	×
	Holes	√√√	××	××
Mobility	High speed	××	√√√	××
Space availability for in house electronics		×××	√√	×××

Indicator

×	Average	××	Poor	×××	Very Poor
√	Good	√√	Very Good	√√√	Excellent

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