The 14th IFToMM World Congress, Taipei, Taiwan, October 25-30, 2015
DOI Number: 10.6567/IFToMM.14TH.WC.OS13.045

A Study of In-pipe Robots for Maintenance of Large-Diameter Sewerage Tunnel

Wei Chuan LAW[1], I-Ming CHEN[2], Song Huat YEO[3], Gim Lee SEET[4], Kin Huat LOW[5]
Mechanical & Aerospace Engineering Department
Nanyang Technological University
Singapore

Abstract: *In-pipe robot is one of the important concepts to achieve automated pipeline maintenance such as inspection, cleaning and repairing. In order to identify available technologies that can perform maintenance of large-diameter sewerage tunnel, a study aimed to review existing pipeline and tunnel robots is then carried out. This kind of robots can be classified into 9 types of robotic system, namely PIG, Wheels, Crawler, Cylindrical, Legs, Inchworm, Helical, Snake and VVPIG type. This study implies that the research on pipeline and tunnel robot has been focusing only on single maintenance task and most of them just aim for small diameter pipelines. In future work, a robot that can perform multifunction for the maintenance of large-diameter sewerage tunnel will be developed.*

Keywords: Pipeline robots, Inspection, Surface Cleaning, Maintenance

I. Introduction

The Deep Tunnel Sewerage System (DTSS) is a public wastewater utility based in Singapore. It is a solution to meet Singapore's long term needs for used water collection, treatment, reclamation and disposal. The DTSS in Singapore comprises of 2 phases: The Phase 1 deep tunnels are now fully operational since 2009 while the target completion period of Phase 2 will be in 2024. Phase 1 of the DTSS consists of a 48km long sewer tunnel from Kranji to Changi up to 6m diameter laid at a depth up to 50m deep across the island. The used water in the deep tunnel sewer is transferred by gravity to the centralized water reclamation plants at the coastal areas[1].

Fig 1. Used water superhighway in Singapore [1]

[1] wclaw@ntu.edu.sg
[2] michen@ntu.edu.sg
[3] myeosh@ntu.edu.sg
[4] mglseet@ntu.edu.sg
[5] mkhlow@ntu.edu.sg

In order to fulfill the task of inspecting the structural integrity of the sewers, cleaning and desilting of sewers, as well as repairing the cracked or damaged sewers that are in normal operation with partially or completely filled condition, a novel robotic system is required. Bischoff & Guhl et al [2] have specifically addressed that there will be large demand on the robots for inspection in dangerous environment or enclosed space in the future. Robotics solutions are advantageous from a worker because it can eliminate the risks that humans always encounter[3]:

- The presence of contagions or biohazardous materials
- Explosive gases
- Possible high concentrations of carbon dioxide or carbon monoxide
- Oxygen deprivation
- Absence of light and slippery walking conditions

Significant research has been done on pipe robot due to its ability to access underground spaces and to achieve easier and better cleaning, inspection and maintenance for deep sewerage tunnel.

II. Pipeline and Tunnel Robots

The pipeline robots can be able to perform a wide variety of tasks ranging from inspection to maintenance and construction. The information gathered from the patents of the pipeline robot has been analyzed and a few broad categories can be classified into nine different robotic systems[4] as shown in the figure below:

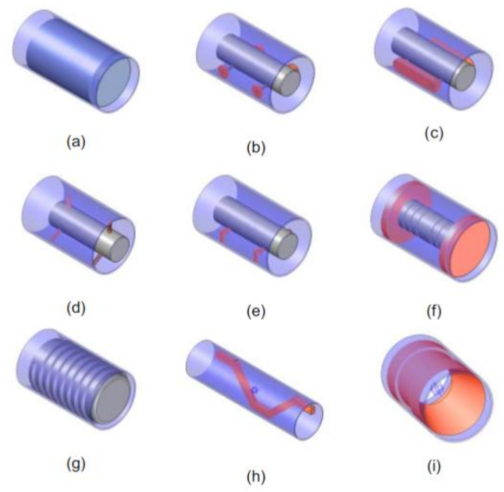


Fig 2. Classification of robotic systems for pipelines. [4, 5]

A. Conventional PIG (Pipeline Inspection Gauge) type

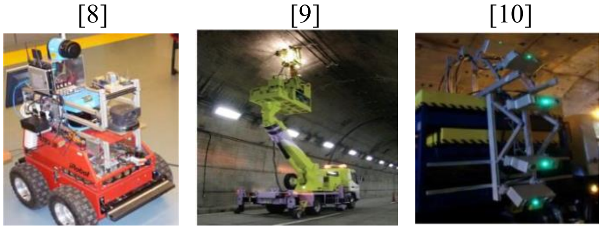
[5, 6] [7]

Fig 3. Conventional PIG Robots

The PIG is a self-drive pipeline robot which obtains its locomotion from the kinetic energy of fluid flow. It is pushed through a pipeline by the product transported in the pipe [7], therefore no power supply is required. During the journey, a number of tasks can be done by PIGs, including: cleaning the pipeline, removal of liquid, and inspection. One of the drawbacks is that this robot needs to be inserted at a specific point in pipeline during the application because it can only move in the direction of the fluid flow.

B. Wheels type

[8] [9] [10]



[11] [12] [13, 14]

Fig 4. Wheels Type Robots

Fig 5. The SVM-RS, a wheel type robot [8]

The SVM-RS [8] is designed to clean and measure damage of a public wastewater utility based in Essen, Germany which will commence operation in 2017. The sewer pipes will range in diameter between 1.6 to 2.6 m with a length of more than 51 km before ending in a large sewage treatment plant. The pipeline will be laid at a depth of 5 to 40 m underground and the maximum distance between entrances of sewer will be around 1.2km.

This robot consists of the main components listed below:

- Carrier system (robot motion kinematics) for positioning in the sewer
- Cleaning tools for cleaning the walls above water as well as the sediment underwater
- Sensor system for above and below water inspection
- A customized buoyant cable is tethered to the robot
- Control system and user interface

MAKRO [9] (Mehrsegmentiger Autonomer KanalROboter/multi-segmented autonomous sewer robot), developed by a German group since 1997, is a self-steering articulated, fully autonomous, un-tethered robot platform. It is designed for autonomous inspection in sewer pipes with a diameter range of 300 to 600mm at dry weather condition. This robot consists of six segments and each segment is connected by a motor driven active joints. Totally five motor driven active joints are used in this design. This segmental design allows robot turning and climbing a step simultaneously. This robot carries all the needed resources onboard, includes industry standard PC104 computer system, standard NiCd batteries, etc.

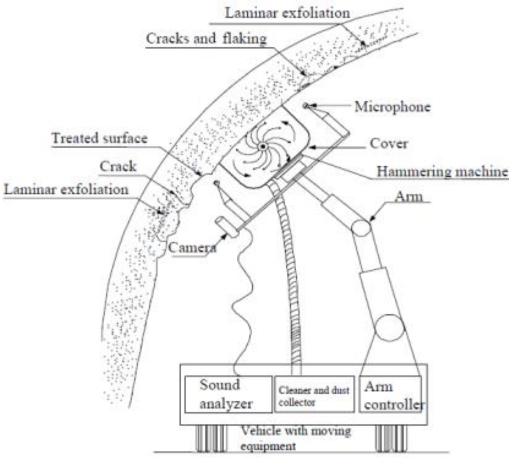


Fig 6. A vehicle is designed for road tunnel inspection [12]

Normally, the road tunnels are visually inspected for cracks, loosening and exfoliation of lining concrete by using a boom lift. However, this conventional method requires a lane to be closed, which is time consuming as well as cracks on arches cannot be detected easily. Therefore, Hideto et al [12] have designed a vehicle equipped with CCD cameras and laser beam to overcome these problems encountered in Japan road tunnel. The images of tunnel surface are captured and then being processed by a system that automatically prepares enlarged diagrams that contain cracks. Besides, the loosening and exfoliation of lining concrete will also be detected by hammering tests performed by the mechanism on the robotic arm.

Fig 7. The Tunneling sensor structure [13, 14]

M. Gavilan et al [14] have developed the Tunneling, a high-performance tunnel lining inspection system which is able to carry out the long tunnel evaluations at travelling speeds up to 30km/h. It analyses the wall linings and railways, allowing for the detection of cracks, areas with running water and poorly assembled segments, etc. Six laser cameras are mounted on an all-terrain truck which provides flexibility to cope with different types of tunnels and infrastructures. Each laser-camera unit inspects a 2-meter wide section with a 1mm resolution. During the inspection, only one half of the tunnel section is covered each time so that the traffic on the free lanes will not be blocked. Thus by using six laser cameras, a tunnel with 9m diameter can be inspected at system's maximum resolution.

C. Crawler type

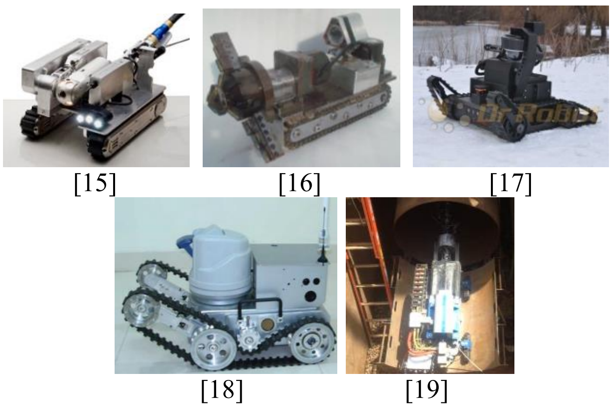


Fig 8. Crawler Type Robots

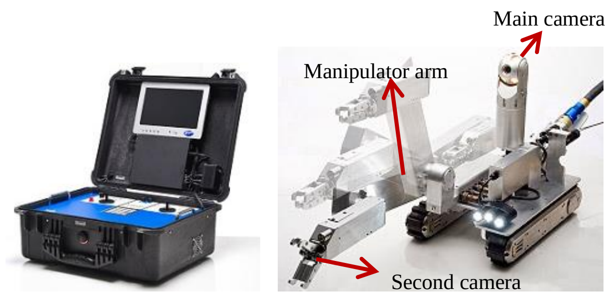


Fig 9. The Versatrax robot [15]

The Versatrax series robot [15] provides wide range of applications, including inspecting many miles of a sewer pipe, searching for survivors after a natural disaster, removing dangerous materials safely, completing assigned task in hazardous environments, etc. The Versatrax robot is applicable either in various diameters of round pipe or flat surface operation. The main camera can be lowered to carry out the navigation in tight spaces or can be raised upright to gain a 360 degree viewing. The manipulator arm integrated with a second camera can be unfolds from the crawler for remote handling of articles while the second camera enables user to monitor the handling operations closely. High output LED lights are mounted on both front and rear of the robot to provide high visibility in low light environments.

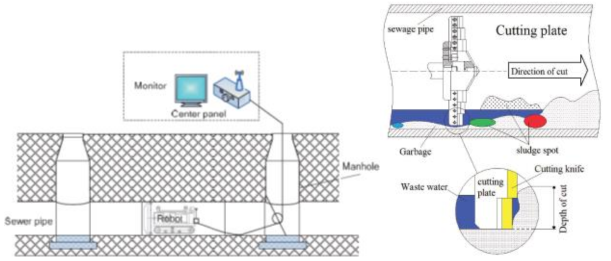


Fig 10. A crawler type pipe cleaning and inspection robot [16]

Nguyen T. T. et al [16] have mentioned that the three most important criteria which allow the in-pipe mobile robot to locomote on and over their deployed terrain are the capability of waterproof, sinkage and the traction on the ground. All these criteria mostly depend on the sludge properties such as granularity, stickiness and hardness, the weight of the mobile robot as well as the contact area and condition between the robot and the terrain.

In order to increase robot traction and stability, as many wheels as possible touching on the ground should be realized. Therefore, a robot is designed by Nguyen T. T. et al [16] based on the tracking mobile robot. The track size should be maximized without affecting the turning ability of the robot to avoid sinkage in dreg or sludge.

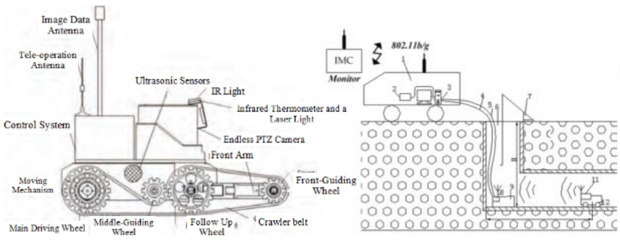
This robot is designed to inspect and clean the Ho Chi Minh City's sewage networks with 300 to 600mm diameter. This design is aimed to shear the rigid dregs or sludge which cannot be removed by high pressure water jet. During the operation, the robot rotates the cutting plate which is mounted on an electrical-powered roller brush to cut off the rigid substances and simultaneously the water jets out from the robot to avoid dust generation. The cutting plate is made of High Speed Steel with a length of 280mm and a width of 30mm. High speed steels are high-performance steels with high wear resistance and they have high hardness at temperature up to 500^{o}C [20].

In this design, a cable is tethered to the robot and the pros of using cable are as follows:

- Provide energy supply and commands transmission
- Enable user to pull the robot out of pipe in case the robot get stuck
- Used as a measuring line for the travelled distance

Fig 11. A crawler robot from DrRobot [17]

DrRobot [17] has pioneered research in autonomous navigation and dynamic bipedal robotics that provides high performance and cost effective robots for end-users. The Jaguar series robot is equipped with a 3 DOF robotic manipulator and a 1 DOF gripper which is able to reach a maximum distance of 707mm. The maximum payload of gripper is 4kg at maximum reach. Four tracked articulated arms mounted on the sides of robot could convert the robot into various configurations to overcome different terrain challenges.



1- The engineering vehicle, 2- The tele-operator/monitor, 3- The UPS, 4- The power cable, 5- The signal cable, 6- The manhole, 7- The hoisting machine, 8- The Wireless transmitter/receiver on ground, 9- The overhead bin, 10- The cable tunnel, 11- The Wireless transmitter/receiver on the robot, 12- The robot

Fig 12. A cable-tunnel inspecting robot with tracks [18]

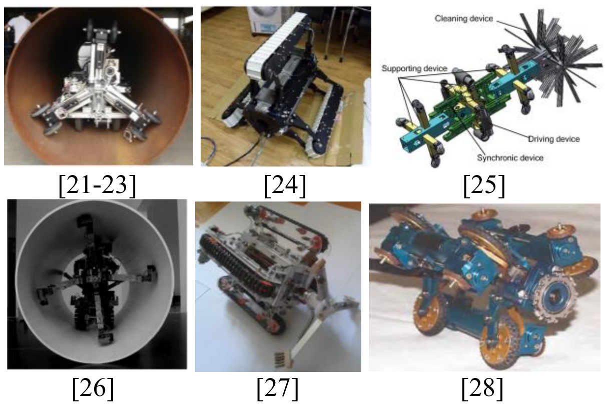
Fu Z. et al [18] have developed a cable-tunnel inspecting robot which consists of a control system and a moving mechanism. A symmetric double-crawler is attached to the moving mechanism. The front arm is able to rotate ranging from 0 to 90 degree. When it needs to be put into tunnel, the robot's front arm will rise to 90 degree to pass through the inlet of small manhole. When it needs to cross an obstacle, the front arm will adjust its angle based on the height of the obstacle.

The system characteristics are as follows:

- The dimension of the main body: 420mm long, 320mm wide and 300mm high (not include the antenna). The front arm is more than 200mm long
- Moving speed > 24m/min
- Robot's weight <3kg
- The height of an obstacle < 100mm
- Working time>2 hour

For a 700x700mm square manhole, a hoisting machine will be adopted to deploy the robot into a cable tunnel by an overhead bin. When the bin is located at the bottom of the manhole, the robot moves out of the bin and drives wirelessly into the cable tunnel. A portable tele-operator in the engineering vehicle is utilized to tele-operate the movement of the robot. An Intelligent Maintenance Center (IMC) is located far apart from the tele-operator. It serves as a monitor to receive the wireless sensing data from the robot through the wireless receiver and the tele-operator so that the environment of the cable-tunnel can be inspected from the real time online system.

D. Cylindrical type



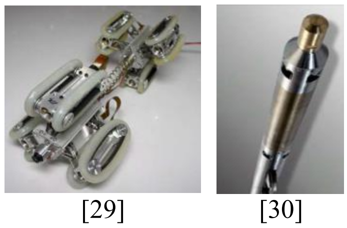


Fig 13. Cylindrical Type Robots

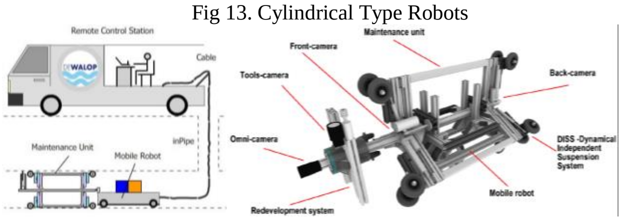


Fig 14. A cylindrical type robot [21-23]

The cylindrical type in-pipe robot [21-23] generally applies pressure on the duct wall to generate necessary traction to support itself along the center of pipe. It achieves pipe cleaning and inspection by holding its structure at the center of pipe and rotating around the inner circumference of the pipe to cover the entire 3D in-pipe space. When the robot is moving out of its centered position, the uneven applied forces of each wheeled leg may break the pipe. Therefore, the robot has to be calibrated at the pipe's center before the corresponding task is implemented.

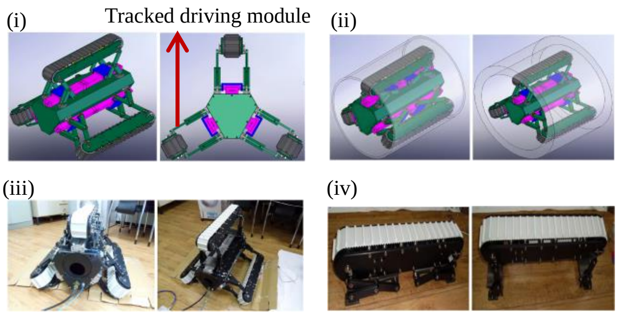


Fig 15. (i) Conceptual design of the in-pipe robot platform; (ii) 3D design of the in-pipe robot with adaptability to different pipe diameters(600-800mm); (iii) Prototype of in-pipe robot; (iv) Track module design [24]

Yoon G.K. et al [24] have developed a robot which is adaptable to different pipe diameters with range of 600 to 800mm. The robot platform is integrated with a modified scissor-lift mechanism controlled by pneumatic cylinder actuators. This mechanism minimizes the distortion forces when the robot passes over obstacles while maximizes the traction forces when the robot pulls the cleaning equipment throughout the pipe. In order to control the pushing force over the pipe wall to obtain its mobility, two linear pneumatic cylinder actuators each equipped with three position sensors are utilized in each tracked driving module. However, more operational functions are required for this robot, such as dynamic adaptation to external disturbances, attitude control and user-friendly remote control. Besides, cleaning tools are also needed to be further developed and integrated into the robot platform.

E. Legs or articulated foot type

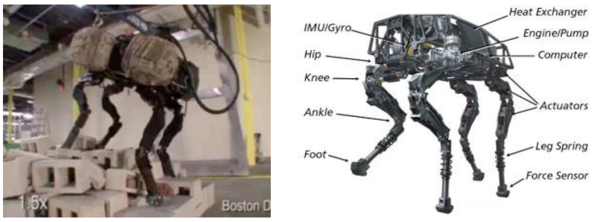


Fig 16. Big Dog from BostonDynamics [31, 32]

Legged robotic systems seemed to be too complicated for practical application, and provide a poor load-carrying capacity [33]. BigDog, developed by BostonDynamics [31], is a four-legged rough-terrain robot that is articulated like animal. The engine drives a hydraulic pump which delivers high pressure hydraulic oil to the robot's leg actuators, so that it is able to absorb shock and recycle energy from one step to the next. The system balances the robot, does navigation and manages locomotion on different terrains. It can stand, walk with a crawling or trotting gait, and squat down. [32]

F. Inchworm type

Fig 17. (i) Cross sectional comparison between an earthworm and a single segment of an earthworm-like robot; (ii) Prototype of the earthworm-like robot [34]

Fang H.b. et al [34] have developed a servomotor based actuation mechanism which mimics the alternating elongation and contraction of a single earthworm's segment. Servomotor-driven cords and spring steel belts are applied in each robot segment to imitate the longitudinal and circular muscles of the earthworm. Each robot segment is able to contract and relax like an earthworm's body segment. Fig 17 shows a multi-segment robot with eight identical segments in series. It is designed to carry out specific tasks in hazardous environment and confined space. In order to adapt to the change of environment, locomotion characteristics such as undesired anchor slippage and average speed can be significantly tailored by changing different gait parameters.

The single segment of this robot consists of two transparent acrylic plates namely head plate and end plate, a servo motor with control horn, two servomotor-driven cords and eight spring-steel belts. A horn is fixed to the servomotor and the servomotor is mounted on the head plate. The crossed servomotor-driven cords route through the two plates and attach to the horn.

When the servomotor is actuated, the horn rotates to a predefined angle and thus tensions the cords. Subsequently the distance between the two plates is reduced and then the spring-steel belts are bent. As a result, the segment is contracted axially and expanded radially. When the servomotor reverses back to its original position, the cords are loosened and the spring-steel belts will spring back and this leads to the recovery of the space between the two plates. Therefore, the segment is extended axially and contracted radially. Each segment can be actuated independently. By alternately actuating the forward and reverse rotational direction of the servomotor, the motion of the robot segment can be achieved in a similar way with an earthworm's body segment.

G. Helical type

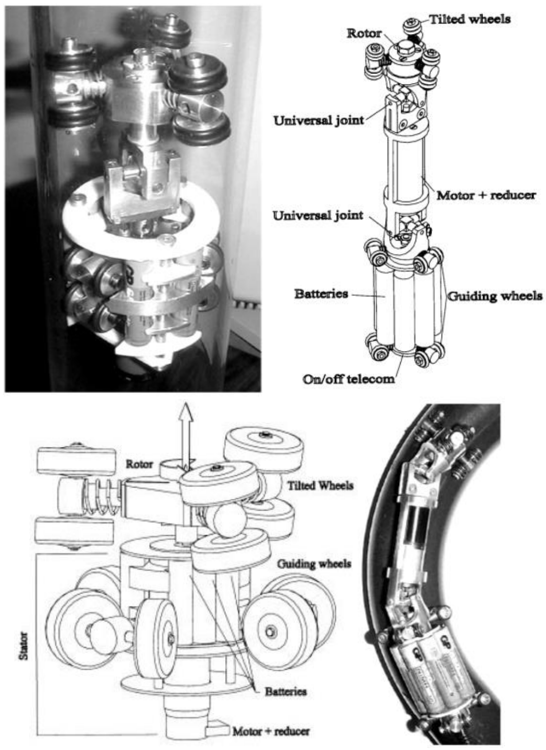


Fig 18. A helical type robot [35]

This robot designed by Horodinca, et al. [35] attempts to reduce the electromechanical complexity by using a single actuator to achieve mobility in the pipeline. The rotor is placed on the shaft of the actuator and the stator is equipped at the back of actuator. When the actuator shaft rotates, the tilted wheels on the rotor follow helical trajectories and drive the entire robot to move forward while the stator follows the movement axially along the tube thanks to the guiding wheels. The actuator's rotational direction decides the moving direction of the robot.

H. Snake type

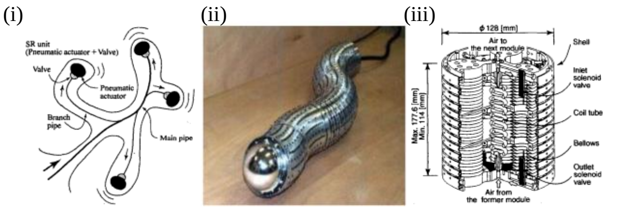


Fig 19. (i) A multi-DOF flexibly-deformable rope-like robot; (ii) Concept of configuration of pneumatically driven system; (iii) The mechanism design of single module [36, 37]

A multi-DOF rope-like robot developed by Hidetaka O. et al [36, 37] is categorized as a hyper-redundant mobile robot. This robot is composed of six serially-connected pneumatic modules where each module consists of pneumatic actuators, displacement sensors, valves, microprocessor and springs. Each module has three bellows which are arranged equally around the circumference and thus it is able to perform 3 DOF motion.

Normally for most of the conventional pneumatically driven robots, the air control valves are mounted outside of the drive mechanism to make it smaller and lighter. However, by doing this way, the robot system composed of many actuators will engage the difficulty of maintaining its shape because all pipelines from pneumatic actuators need to be arranged to the valves outside of the drive mechanism. Therefore, in each module, six on-off solenoid valves for the inlet and outlet of air are mounted at each end of the bellows respectively. A main pipe for compressed air supply is connected into the body of the robot. The compressed air is provided into each bellow through the branch pipe. By controlling the air intake of each bellow through the control valve, the module can achieve the desired motion.

The features of each module mechanism are as follows:

- Compressed air distribution mechanism reduces the number of pipes and tubes used
- Pneumatically driven system is utilized to save electrical power
- Bellows drive system with buckling prevention
- Shell mechanism with limited displacement
- Installation of modularized system

I. Variable velocity PIG type

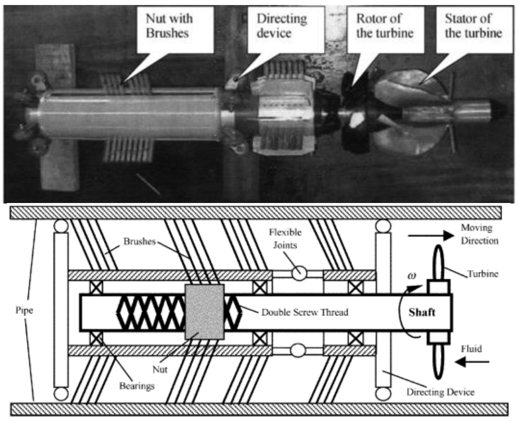


Fig 20. Basic structure of hydraulic brush PIG [33]

Generally, it is very hard for wheels robotic systems to generate enough traction force to move against a fluid with high flow rate. Therefore, a VVPIG robot is designed by Zheng Hu et al [33] to move with and against the direction of the flowing fluid in the pipe effectively via a turbine and a reverse-traverse screw mechanism. This design is distinguished from the conventional PIG type of robot which can only follow the flowing fluid. Many oil and gas industries benefit from this robot of its valuable bidirectional capability.

The directing device integrated with wheels keeps the robot in the middle of the pipe. The reverse-traverse screw thread mechanism transforms the rotational torque of the turbine which generated by the fluid flow into the translational propulsion force for robot movement. Besides, the reversing nature of the screw converts the turbine's rotating motion into the nut's reciprocating motion on the shaft. Due to the fact that the brushes with rearward-pointing bristles can move forward easily but are difficult to move backward, the robot can be able to crawl upstream or downstream depends on the initial direction of the bristles.

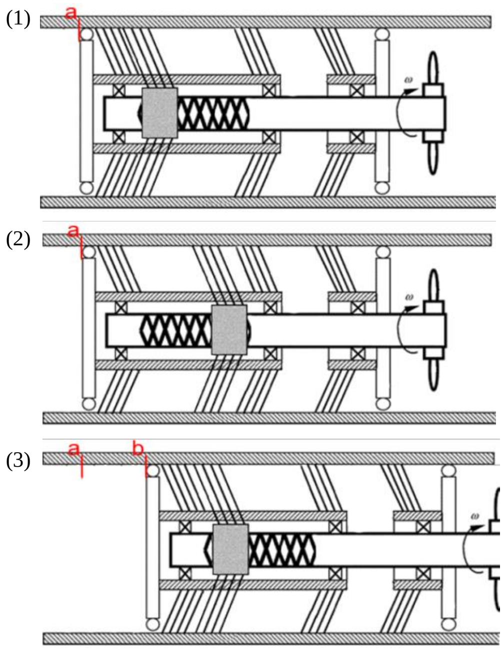


Fig 21. The motion of VVPIG robot from point a to b

As shown in Fig 21, the working principle of the mechanism is as follows:

(1) The turbine is rotated by the fluid flow, and which will then drive the transmission shaft rotating at the same speed.

(2) When the nut is in the forward driving screw thread, it will be pushed forward (to the right) because the brushes attached to the nut can be able to slide forwards while the brushes on the body of the PIG is stationary against the pipe wall.

(3) When the nut arrives at the end of the screw thread, the nut will be moving backward conversely. Since the rearward-pointing brushes on the nut are hardly to be moved backward, the robot body will begin to move forward instead.

A comparison between various types of Pipe and Tunnel Inspection Robot is shown in the table next page.

Type	Pros	Cons	Robot	Capability	Applicable Pipe Size (mm)
PIG	• Simple mechanism design • No power supply required	• Keep rotating along its central axis when moving • Poor performance on various conditions like low fluid flow or complex pipe system • Only moves along the direction of fluid	[5, 6]	Inspection	ϕ25-150
			[7]	Inspection	-
Wheels	• Common design • Low maintenance costs • Lower cost than tracks	• Complex steering mechanism • Poor performance on certain terrains • High centering when travelling over uneven terrain	[8]	Inspection, Cleaning	ϕ 1600-2600
			[9]	Inspection	ϕ 300-600
			[10]	Inspection, Cleaning	-
			[11]	Inspection	-
			[12]	Inspection	-
			[13, 14]	Inspection	ϕ 9000
Crawler	• Handles more aggressive terrain	• Less energy efficiency • Expensive	[15]	Inspection	Min. 381
			[16]	Inspection, Cleaning	ϕ 300-600
			[17]	Inspection	-
			[18]	Inspection	700x700
			[19]	Repairing	ϕ 152.4-4419.6
Cylindrical	• Able to move forward and backward freely in small diameter pipe • Adaptable to small pipes with different diameters	• Calibration at the center of pipe is needed before the operation • Mainly suitable for precise motion in small pipe • Not suitable for complex pipe structures with low payload	[21-23]	Inspection, Cleaning	ϕ 800-1000
			[24]	Inspection	ϕ 600-800
			[25]	Cleaning	Rectangle 300-600
			[26]	Inspection, Cleaning	ϕ 300-600
			[27]	Cleaning	ϕ 150
			[28]	Inspection	ϕ 100
			[29]	Inspection	ϕ 80-100
			[30]	Inspection	-
Legs	• Able to cope with different in-pipe environment	• Relatively complicated for practical application • Provide poor load-carrying capacity • Instability during locomotion	[31, 32]	-	-
Inchworm	• Light weight • Cheap	• Not effective due to its low speed • Poor reliability	[34]	-	ϕ 103.5
Helical	• Relatively less actuators needed • Able to move forward and backward freely in small diameter pipe	• Not effective due to its low speed • Mainly suitable for precise motion in small pipe • Not suitable for complex pipe structures with low payload	[35]	Inspection	ϕ 40-170
Snake	• No motors and wheels needed • Move horizontally like normal wheeled robot motion	• Need more energy for operation	[36, 37]	-	-
VVPIG	• No power supply required • Able to move with either along or against the direction of the flowing fluid	• Poor performance on various occasions like low fluid flow or complex pipe system	[33]	Cleaning	-

Table 1. Comparison of pipeline robotic systems

III. Conclusions

This article reviewed a series of in-pipe robots and classified the types of the robot base on the locomotion mechanism. After reviewing the available technologies for maintenance of deep large sewers, for the time being we cannot identify any single robotic technology that can effectively combine all the desired functionalities such as inspection, cleaning and repairing into single unit. Most of the existing robots are for small or medium pipelines. From the survey, the system design of SVM-RS[8] with inspection and cleaning function for medium tunnel seemed to be also suitable for large-diameter sewerage tunnel. In future work, a robot that is able to perform tunnel inspection, cleaning and maintenance for large-diameter sewerage tunnel will be developed.

References

[1] http://www.pub.gov.sg/dtss/PublishingImages/, November 2014.

[2] R. Bischoff and T. Guhl, "The strategic research agenda for robotics in Europe," *IEEE Robotics & Automation Magazine*, vol. 17 (1), pp. 15-16, 2010.
[3] C. Walter, J. Saenz, N. Elkmann, H. Althoff, S. Kutzner, and T. Stuerze, "Design Considerations of Robotic System for Cleaning and Inspection of Large-Diameter Sewers," *Journal of Field Robotics* vol. 29(1), 2012.
[4] J. F. Archila and M. Becker, "Study of Robots to Pipelines, Mathematical Models and Simulation," *IEEE Latin American Robotics Symposium*, pp. 18-23, 2013.
[5] J. F. Archila, M. S. Dutra, J. C. Pinillos, and K. M. Cantero, "Study of pipeline inspection robots and numeric simulation inside service pipes," p. 8.
[6] C. A. Marinho, C. Patusco, C. Camerini, L. Mesquita, R. W. d. Santos, S. Damasceno, *et al.*, "Petrobras' developments in underwater inspection," *8th World Conference on Nondestructive Testing*, 16-20 April 2012.
[7] http://business.financialpost.com/2013/03/02/pipelines-in-canada-sophisticated-arteries/?__lsa=cd4e-3b98/, November 2014.
[8] J. Saenz, N. Elkmann, T. Stuerze, S. Kutzner, and H. Althoff, "Robotic systems for cleaning and inspection of large concrete pipes," *2010 1st International Conference on Applied Robotics for the Power Industry*, 5-7 October 2010.
[9] A. Ahrary, "Sewer Robotics," *Service Robot Applications, Yoshihiko Takahashi (Ed.)*, 2008.
[10] A. Ṣteopan, M. Steopan, and A. Nicu, "Competitive Design and Mockup of a Modular Pipe Cleaning Mobile Equipment."
[11] J. Bedkowski, P. Kowalski, J. Piszczek, and A. Masłowski, "ATRVJr – mobile robot for Fire Fighter Services."
[12] H. Mashimo and T. Ishimura, "State of the art and future prospect of maintenance and operation of road tunnel," *ISARC2006*.
[13] C. Balaguer, R. Montero, J. G. Victores, S. Martínez, and A. Jardón, "Towards Fully Automated Tunnel Inspection: A Survey and Future Trends," *The 31st International Symposium on Automation and Robotics in Construction and Mining (ISARC 2014)*, 2014.
[14] M. Gavilán, F. Sánchez, J. A. Ramos, and O. Marcos, "Mobile Inspection System For High-Resolution Assessment of Tunnels," *The 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure, Hong Kong*, 9-11 December 2013.
[15] http://www.inuktun.com/crawler-vehicles/, October 2014.
[16] N. Truong-Thinh, N. Ngoc-Phuong, and T. Phuoc-Tho, "A study of pipe-cleaning and inspection robot," *IEEE International Conference on Robotics and Biomimetics*, 7-11 December 2011.
[17] http://www.drrobot.com/, October 2014.
[18] F. Zhuang, C. Zupan, Z. Chao, and Z. Yanzheng, "A cable-tunnel inspecting robot for dangerous environment," *International Journal of Advanced Robotic Systems*, vol. 5, pp. 243-248, 2008.
[19] http://www.questinspar.com/, January 2015.
[20] http://www.erasteel.com/content/conventional-high-speed-steel/, January 2015.
[21] L. A. Mateos and M. Vincze, "DeWaLoP In-Pipe Robot Position from Visual Patterns," *MICAI 2012, Part I, LNAI 7629*, pp. 239–248, 2012.
[22] L. A. Mateos, K. Zhou, and M. Vincze, "Towards Efficient Pipe Maintenance: DeWaLoP In-pipe Robot Stability Controller," *2012 IEEE International Conference on Mechatronics and Automation*, 5 - 8 August 2012.
[23] L. A. Mateos, M. R. y. Dominguez, and M. Vincze, "Automatic In-pipe Robot Centering from 3D to 2D Controller Simplification," *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 3-7 November 2013.
[24] Y.-G. Kim, D.-H. Shin, J.-I. Moon, and J. An, "Design and Implementation of an Optimal In-pipe Navigation Mechanism for a Steel Pipe Cleaning Robot," *8th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI 2)*, vol. Nov. 23-26, 2011.
[25] C. Ye, S. Ma, H. Li, and J. Yang, "Development of a Pipe Cleaning Robot for Air Conditioning System," *2010 IEEE International Conference on Robotics and Biomimetics*, pp. 1525-1529, 14-18 December 2010.
[26] Z. Li, J. Zhu, C. He, and W. Wang, "A New Pipe Cleaning and Inspection Robot with Active Pipe-diameter Adaptability Based on ATmega64," *The Ninth International Conference on Electronic Measurement & Instruments*, pp. 2-616 To 2-619, 2009.
[27] S. N. B. Mohamad, "Fully autonomous pipeline cleaning robot," *Thesis of the degree of Bachelor of Engineering (Electrical - Mechatronics)*, July 2012.
[28] S.-g. Roh and H. R. Choi, "Differential-Drive In-Pipe Robot for Moving Inside Urban Gas Pipelines," *IEEE Transactions On Robotics*, vol. 21, p. 17, February 2005.
[29] Y.-S. Kwon, H. Lim, E.-J. Jung, and B.-J. Yi, "Design and Motion Planning of a Two-Moduled Indoor Pipeline Inspection Robot," *IEEE International Conference on Robotics and Automation*, p. 397, 19-23 May 2008.
[30] D. Feng, S. Li, J. Liu, P. Wang, K. Zhou, and C. Huang, "Research on Key Technology in Downhole Crawling Robot," *IEEE International Conference* pp. 536 - 539, 2009.
[31] http://www.bostondynamics.com/robot_bigdog.html, November 2014.
[32] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, and t. B. Team, "BigDog, the Rough-Terrain Quaduped Robot," 2008.
[33] Z. Hu and E. Appleton, "Dynamic Characteristics of a Novel Self-Drive Pipeline Pig," *IEEE Transactions On Robotics*, vol. VOL. 21, pp. 781-789, October 2005.
[34] H. Fang, C. Wang, S. Li, J. Xu, and K. W. Wang, "Design and experimental gait analysis of a multi-segment in-pipe robot inspired by earthworm's peristaltic locomotion," *Proc. of SPIE*, vol. Vol. 9055, 90550H, 2014.
[35] M. Horodinca, I. Doroftei, E. Mignon, and A. Preumont, "A simple architecture for in-pipe inspection robots," *Colloquium on Mobile and Autonomous Systems, 10 Years of the Fraunhofer IFF*, June 2002.
[36] H. Ohno and S. Hirose, "Design of Slim Slime Robot and its Gait of Locomotion," *International Conference on Intelligent Robots and Systems*, 29 Oct. - 03 Nov. 2001.
[37] H. Ohno and S. Hirose, "Study on Slime Robot (Proposal of Slime Robot and Design of Slim Slime Robot)," *2000 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2000.