Design Concept and Motion Planning of a Single-Moduled Autonomous Pipeline Exploration Robot

Jong-Hoon Kim†, Gokarna Sharma†, and S.S. Iyengar†
† Robotics Research Laboratory, Department of Computer Science
Louisiana State University, Baton Rouge, LA 70803, USA
jkim24@lsu.edu, {gokarna, iyengar}@csc.lsu.edu

***Abstract*—In this paper, we present the design concept and motion planning of a single-moduled fully autonomous mobile pipeline exploration robot that can be used for the inspection of Φ130∼150mm pipelines. In this robot, the four straight wall-press caterpillar wheels are fixed 90 degrees apart in its circumstance and each wheel is operated by two DC motors integrated in it. The speed of each wheel is controlled independently to provide steering capability to go through 45 degree elbows, 90 degree elbows, T-branches, and Y-branches. The robot system has been developed and experimented in different pipeline layouts for the validation of its design concept and motion planning mechanism.**

I. Introduction

Robot agents have been considered as an attractive alternative to detect and locate any leakage, damage, or corrosion in pipeline systems for many years. A number of different pipeline robots has been proposed in the literature to serve that purpose, some of them are [1]–[10]. While a huge number of aforementioned robot based systems ([1], [2], [3], [4], [5], [6], [7]) are manually controlled, rest of them ([8], [9], [10]) considered semi-autonomous/autonomous solutions. Although many different types of pipeline exploration robots (manual/semi-autonomous/autonomous) have been proposed, they were suffered from various limitations. This is because most of the aforementioned pipeline robots have only been tested at straight and simply curved pipelines. Some of them, which have demonstrated good performance in T- and Y-branches, are not space-efficient and prone to wheel slip errors; and some of them have no vertical mobility at all.

In this paper, we present the design concept and motion planning of a single-moduled wall-press straight caterpillar-based fully autonomous mobile pipeline exploration robot that can be used for the inspection of Φ130∼150mm pipelines. It consists of four straight caterpillars fixed 90 degrees apart in its circumstance and operated by two DC motors each. The speed of each caterpillar is controlled independently to provide steering capability to go through 45 degree elbows, 90 degree elbows, T-branches, and Y-branches. The robot system has been designed, implemented, and experimented in different pipeline layouts for the validation of its design concept and motion planning mechanism.

II. Characteristics

This particular design of the fully autonomous mobile pipeline exploration robot focuses on verification of the mobility mechanism in complex pipeline layouts consisting of different pipeline bends, and vertical and horizontal geo-spatial conditions with manual controlling system using Gumstix-based devices. The robot is implemented as a straight caterpillar-based wall-press robot for the efficient navigation and inspection of Φ130∼150mm pipelines. The robot consists of a main body, caterpillar wheel parts, four extendable link systems, and other attached functions as demonstrated in Fig. 1. The attached functions are composed of different sensing, communication, and actuation devices as per the pipeline inspection demands. The length of the robot is 148mm and the exterior diameter is 127mm at maximum shrinking condition and 157mm at normal condition.

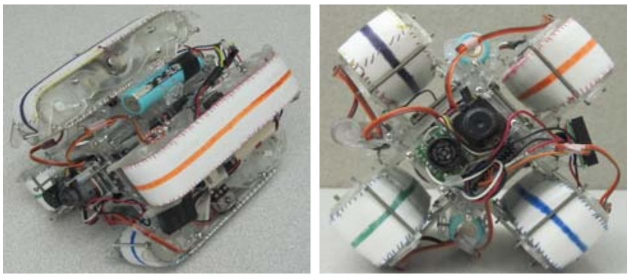


Fig. 1: The autonomous pipeline exploration robot

The main body consists of a Gumstix board extended by some expansion boards with the required communication, sensing, and reaction capabilities and a extendable link structure which connects the main body to the caterpillar wheels. The interface board provides interface to the micro-controller, compass, 3D-accelerometer, rotary encoder, and Li-ion battery used in the robot. The body is constructed as a square shape, which is adequate to support the four extendable link systems and the size of the central body frame is 40mm×40mm×108mm. The caterpillar wheel is made of two motors attached one on each side of the wheel, a rotary encoder, and a wrapping belt. Each caterpillar wheel is arranged 90 degrees apart and each of which are 33mm wide and 148mm long. Below we present the summary of the robot characteristics and focus primarily on its motion planning mechanism, the detailed description of its characteristics can be found elsewhere [11], [12].

Caterpillar mechanism. The distance between the central body of the robot and the caterpillar wheels can be determined

978-1-4244-5226-2/10/$26.00 ©2010 IEEE

based on the movement of the flexible links, the elastic restoration force on the spring at each suspension link, and reaction forces from the wall. Each of the four caterpillars is able to hold the surface of the pipeline firmly while moving inside the pipeline very smoothly. The steering capability to go through 45 degree elbows, 90 degree elbows, T-branches, and Y-branches is provided by controlling the speed of each caterpillar independently through differentiating the speeds of the four caterpillars. The rotary encoder equipped in each caterpillar wheel calculates the distance moved so far and a set of two geared motors, two pulleys, and a belt transmits the driving power to the caterpillar. Moreover, the wall-pressing mechanism is developed to make the robot climb up and down in vertical situations. To achieve efficient wall-pressing mechanism, each caterpillar wheel is mounted to the central body using four independent suspension links. These links are responsible for giving the required gripping force to the robot and the robot can be contracted from 157mm to 127mm using these links. The suspension link's ability to contract and expand make the robot flexible enough to move through the highly-bent pipelines.

Operational architecture. The operational architecture of the robot is given in Fig. 2 which consists of three operator modules: (a) Supreme Operator (SO); (b) Perception Operator (PO); and (c) Action Operator (AO). Each operator has different manager modules which perform fundamental operations with their own property values. The property values are stored in a central repository which can be referred and updated by the module which is accessing them and/or any other operator/s based on some predetermined rules. This modular ability of the architecture enables each module to be developed and extended independently. These property values can be changed by SO or PO depending on the environmental conditions or any other operator which might require to do so to perform its action. The central repository also contains the predefined rules, sensed data, map information, results of actions, and history of events of each operators. SO sends the decision message to AO to perform necessary actions. SO might also tune the property values of AO to make the action being performed by AO adaptable to the environment with time based on the indirect real-time feedback from PO. These messages can be feedbacked indirectly and receiver's property values can be tuned by the sender using those feedbacks.

Control architecture. The control architecture of the robot as depicted in Fig. 3 illustrates motor speeds for all four caterpillars depending on the direction in which the robot is intended to turn. For example, if the robot wants to move forward in a straight pipeline, all wheels rotate in same direction with equal speed but when if it wants to turn 90 degrees, CM sets the motor speed of wheel 1 to 0 and motor speed of wheels 2, 3, and 4 to 10 based on the property values provided in Fig. 3. The robot can also monitor the wheel slipping in certain pipeline conditions and adjust the motor speeds based on the feedback generated by PO to cope with such situations.

Electrical architecture. The electrical architecture of the robot given in Fig. 11 consists of four main components: (a) Interface Board (IB); (b) Expansion Board (EB); (c) Gumstix Main Board (GMB); and (d) Sensors and Controllers. IB is used to provide efficient and easy connection to all the sensors and some of the controllers; when one or more sensors are damaged then they can be replaced without disassembling the entire robot. It can also be used to connect all the expansion modules on to their respective interface boards. IB also regulates voltages of all devices and removes noises from DC motors. As Gumstix does not have in-built modules needed for communication, we integrated some expansion boards with the required communication, sensing, and reaction capabilities; some of which used in the robot are WIFI-Stix and Robostix.

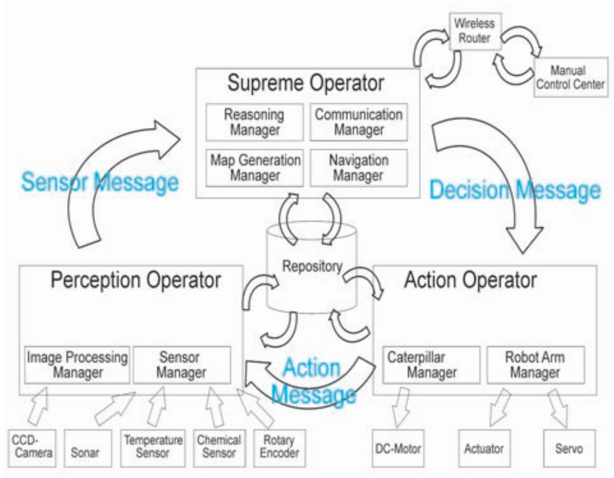


Fig. 2: Operational architecture of the robot

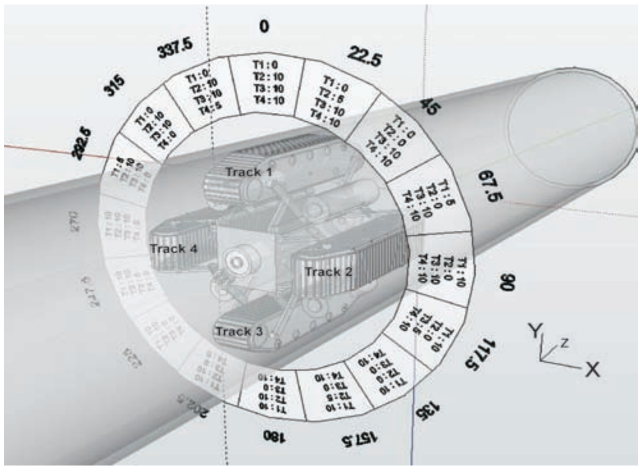


Fig. 3: Control architecture of the robot

Different sensing and controlling functions are also implemented in the robot to make it fully autonomous and mobile in pipeline inspection and exploration. A compass is integrated for obtaining the direction in which the robot is heading, a 3D accelerometer is used to get its tilt information, and a sonar is used to determine the obstacle or hole position in the pipeline.

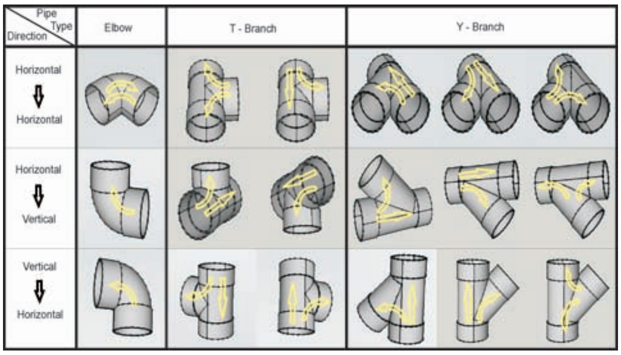


Fig. 4: Different types of motion in elbow, T-, and Y-branches

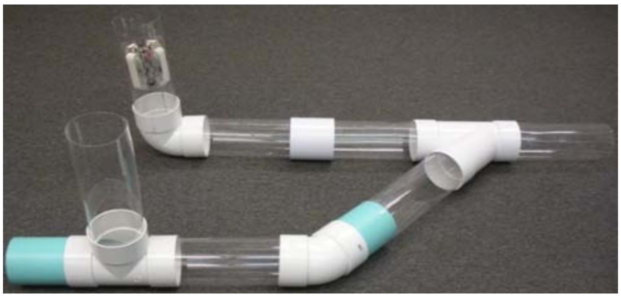


Fig. 5: Experimental pipeline layout

III. Motion Planning of The Robot

We performed several experiments to check motion capability of the robot at 45 and 90 degrees elbows, T-, and Y-branches. At 45 and 90 degrees elbow, there are 3 types, at T-branch, there are 16 types, and at Y-branch, there are 24 types of motion. Different types of robot motion in different pipeline bends (45 and 90 degrees elbows, T-, and Y-branches) are given in Fig. 4.

A. Experimental Testbed

The experimental pipeline layout is given in Fig. 5. It is constructed including all possible pipeline bends and contains one 45 degrees elbow, one 90 degrees elbow, one T-branch, and one Y-branch. The inside diameter of the sewer pipeline used in the experimental pipeline layout is 150mm. First, the robot is evaluated in different pipeline bends separately. Later, the robot will be evaluated in a complex pipeline layout of Fig. 5.

B. Motion Planning

Motion planning at 45 degrees elbow. The motion planning of the robot at 45 degrees elbow is similar to the motion planning of 90 degrees elbow given below.

Motion planning at 90 degrees elbow. The motion planning of the robot at 90 degree elbow is given in Fig. 6. The robot make a turn by making stationary the wheels contacting the inner corner of the 90 degrees elbow and rotating the wheels contacting the outer side of the 90 degrees elbow toward vertical or horizontal direction it intends to turn.

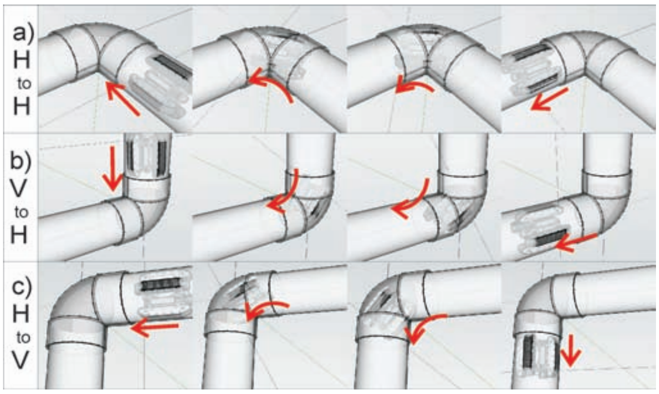


Fig. 6: Motion planning at 90 degrees elbow, where H to H indicates Horizontal to Horizontal, V to H indicates Vertical to Horizontal, and H to V indicates Horizontal to Vertical motion

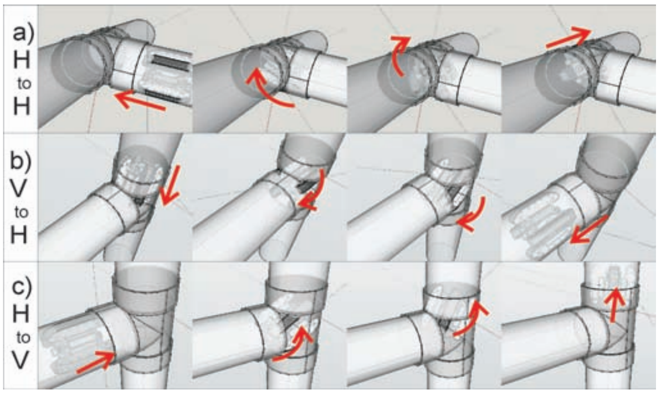


Fig. 7: Motion planning at T-branch

Motion planning at T-branch. The motion planning of the robot at T-branch is given in Fig. 7. It has been observed that motion planning at T-branch is more complicated since there are many paths at T-branch. From our experiments, the transition from the horizontal to the vertical motion inside the pipeline is found to be the most difficult scenario. This is due to the small area of contact for the caterpillar wheels to be able to make contact to the inside wall of the pipeline. When there is a very small area of contact, the robot wheels cannot apply the functionality of differentiating the caterpillar's speed for making a turn. The depiction of the pipeline surface contact by the caterpillar wheels at T-branch for the successful motion is given in Fig. 8, where the circled parts denote the contact areas. In the scenarios depicted in the figure, the robot can make a turn by making stationary the wheels contacting the inner corner of the T-branch and rotating the wheels contacting the outer corner of the T-branch toward the vertical side. The control architecture of the robot described in Fig. 3 provides the functionality of controlling the motor speeds to achieve such scenarios.

Motion planning at Y-branch. The motion planning of the robot at Y-branch is given in Fig. 9. The motion planning in Y-branch is relatively easy in comparison to T-branch, so we skip the discussion here.

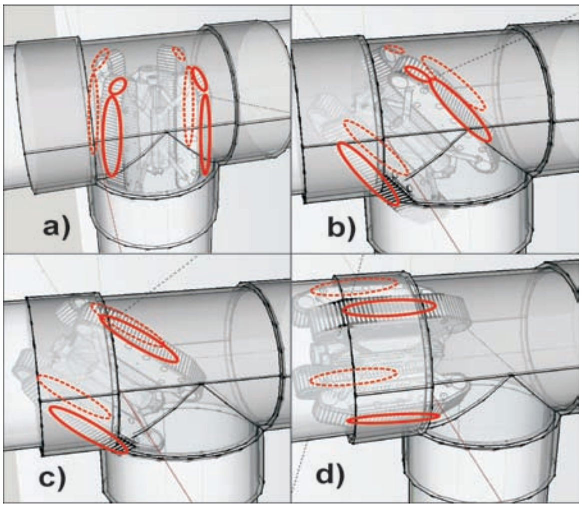


Fig. 8: Depiction of the pipeline surface contact by robot wheels at T-branch

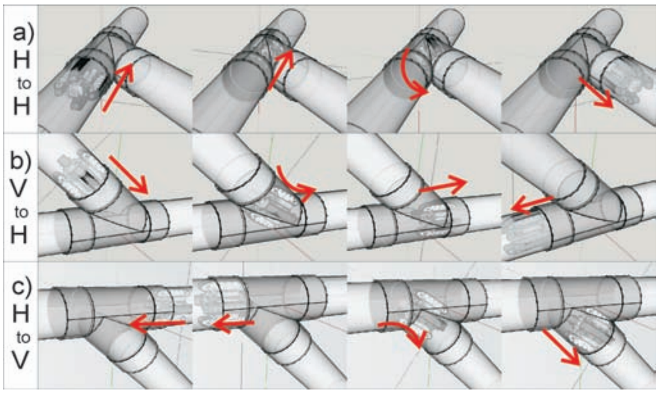


Fig. 9: Motion planning at Y-branch

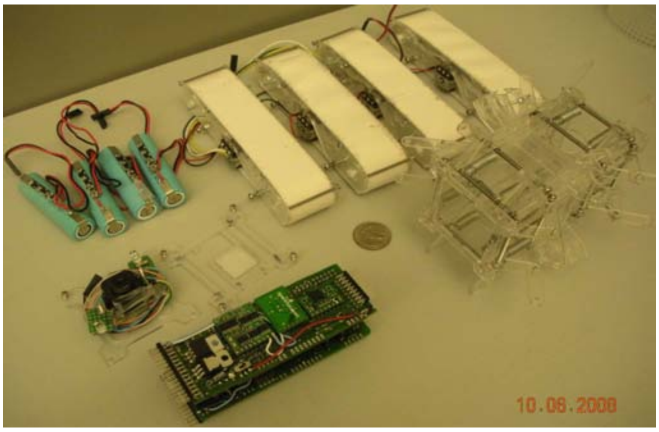


Fig. 10: Components of the robot

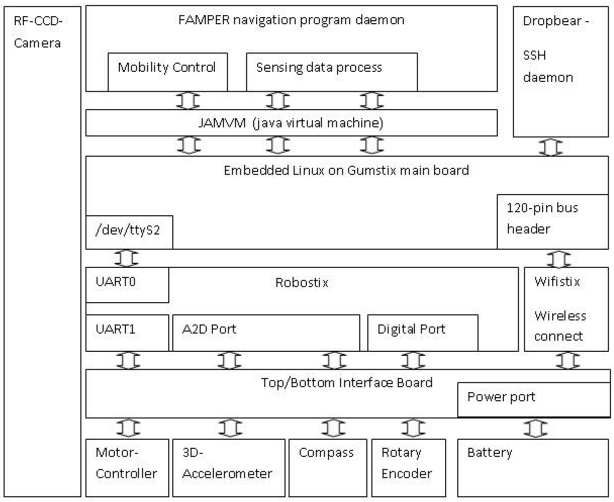


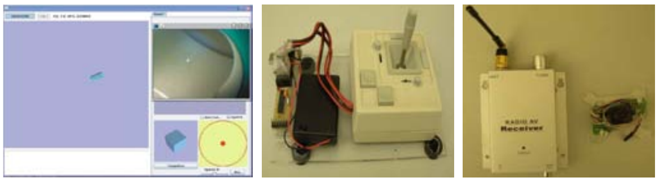
Fig. 11: Electrical architecture of the robot

IV. Implementation

Hardware platform. The components of the robot are given in Fig. 10. A small but powerful computing system based on Gumstix main board is assisted by two interface boards: Robostix and WiFi-stix. They are interconnected to all the internal ports of the Gumstix, Robostix, and WiFi-stix, and also with the attached sensors and external controllers. They also regulate the power for all the internal boards. This layout gives easy and universal access to all the ports available in front and rear part of the central body system.

The robot has attached RF-CCD Camera, which can send the video stream independently, and the sensors such as a 3D-accelerometer, a compass, and a rotary encoder for particular purposes. Robostix provides the required pins to read data from available sensors by forwarding them to the Gumstix after converting them from analog to digital. WIFI-Stix adds the functionality of transmitting and receiving data to and from a remote computer using wireless network. Gumstix is installed with embedded Linux platform which has the capability of running programs written on high level languages. In this implementation, we programmed the controlling interface using Java. The sensor readings have been read using programs written in AVR-C which are later ported to the Robostix.

User control interface. A Manual Control Program (MCP) has been developed to operate the robot in different pipeline layouts. The program comprises of four major panels: (a) 3D view of the robot's position; (b) RF video panel to display video stream from RF camera; (c) Control Panel (CP) to control the robot using the the robot Controller (FC) and/or the GUI interface and to provide the tilting and direction of the robot as indicated in mini 3D view; and (d) Message Console (MC) to display the detailed status of the robot. The controlling signals are sent to the computer running the MCP using FC as given in Fig. 12. FC uses an analog joystick and also provides flexibility of sending the control signals using Bluetooth and USB connections. In order to control the robot from a remote location, we used RF video system which is small in size, consumes low power, and have high sensitivity in inspecting the situations inside the pipeline. We have also added ultra bright LEDs which help the RF video camera system to capture the robot environment.



(a) Manual control program (b) FC Controller (c) RF video system

Fig. 12: Controlling and RF video system

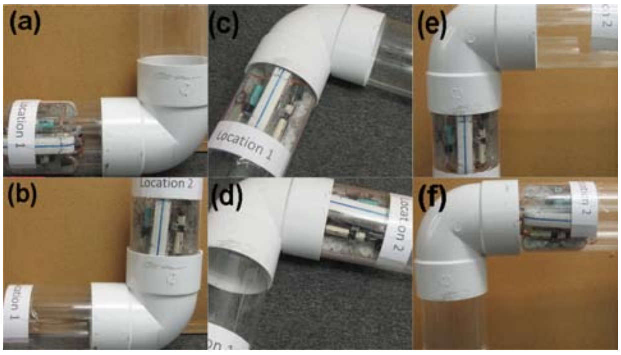


Fig. 13: Types of motion at 90 degrees elbow, where (a), (b) show H to V, (c), (d) show H to H, and (e), (f) show V to H motion

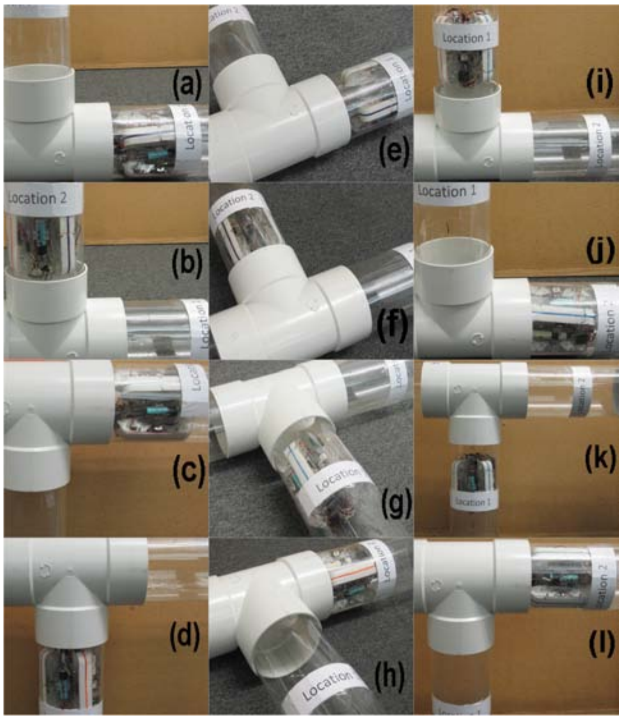


Fig. 14: Types of motion at T-branch, where (a)-(d) show H to V, (e)-(h) show H to H, and (i)-(l) show V to H motion

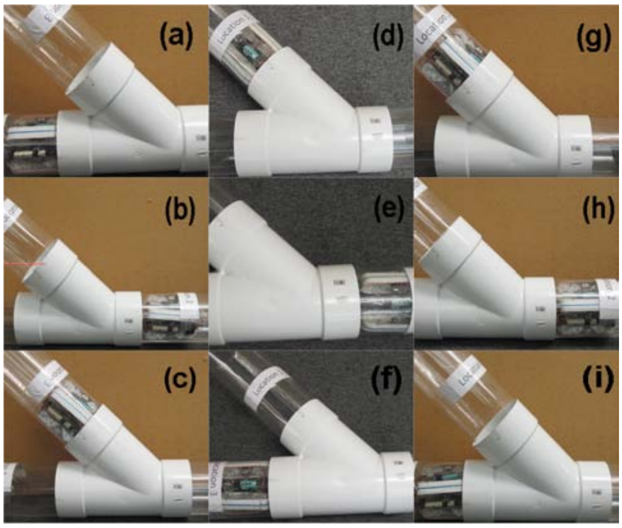


Fig. 15: Types of motion at Y-branch, where (a)-(c) show H to V, (d)-(f) show H to H, and (g)-(i) show V to H motion

V. Experiments

For the experimental evaluation, the robot is employed in the inspection of a complex pipeline layout, that has been constructed using all available pipeline fittings that a typical pipeline system uses, where the robot also needs to perform vertical and horizontal motion. Recall that one of such complex pipeline layout used in the experiments is given in Fig. 5. The robot is first experimented in each bends individually and then experimented to the whole pipeline layout. The robot manages to travel through the layout by changing the motor speed appropriately. The Fig. 13 shows that the pipeline exploration robot is traveling to several directions (including climbing up and down in the vertical pipeline) in the 90 degrees elbow of the experimental pipeline layout (types of motion at 45 degrees elbow is similar). The Fig. 14 shows that the robot traveling to several directions in a T-branch of the experimental pipeline layout. Similarly, the Fig. 15 shows that the robot traveling to several directions in a Y-branch of the layout. The video clip available here [13] shows the performance result of the robot in the whole pipeline layout.

VI. Performance Analysis

Analysis of singular motion. In this section we discussion the motion singularity conditions we observed in the experiments. The motion singularity problem [7] has been observed for some of the cases while the robot was passing through T-branches because the robot looses contacts at turning position as shown in Fig. 16. This is because the two caterpillar wheels are not able to contact the surface of the pipeline (the $\times$ denotes the no contact points which are indeed need to be in contact to the pipeline surface for successful motion). However, after several round of experiments using several configurations of the caterpillar wheels of the robot at T-branch, we have concluded that the robot can be able to turn in all pipeline layouts when at least three caterpillar wheels can manage to be in contact with the pipeline surface as illustrated in Fig. 8. Moreover, in the conditions where only two caterpillar wheels can contact the pipeline surface, the robot can turn in all possible configurations except only two

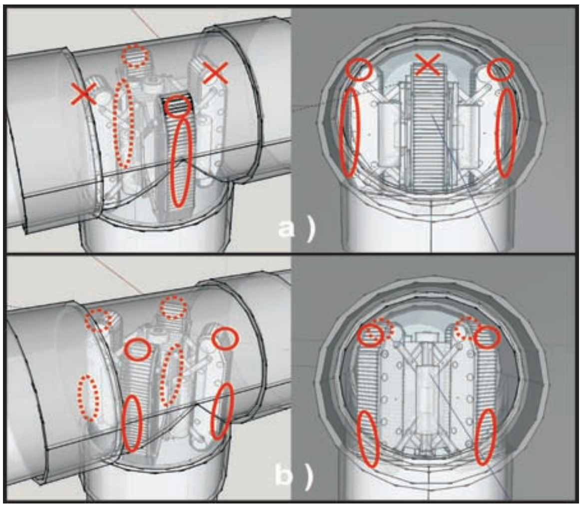


Fig. 16: Motion singularity problem, where (a) depicts singular motion and (b) depicts successful motion

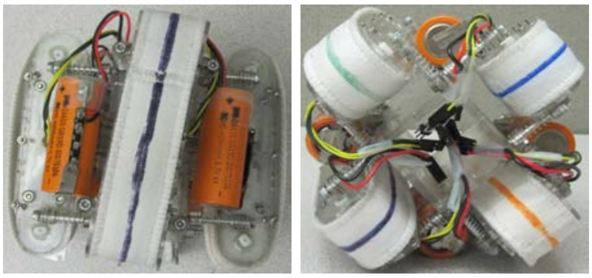


Fig. 17: The 5 degrees tilted caterpillar-based robot design

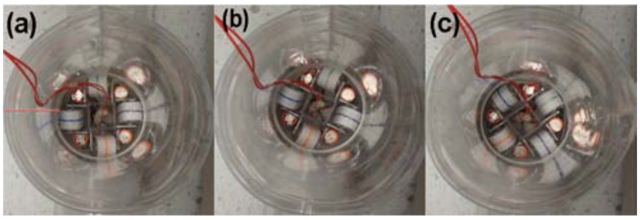


Fig. 18: Self-adjusting from motion singularity position to successful motion position

caterpillar wheels in the diagonal are in contact with pipeline surface. The problem stems from the fact that the straight caterpillar mechanism does not exhibit the capability of self-adjustability from the position where it cannot able to make a turn (unsuccessful position) to the position where it eventually can make a turn (successful position). Nevertheless, we also observed from the experiments that if the robot can self-adjust to the position where robot can eventually make three or more of its caterpillars contact the surface, then it can change direction at T-branches.

Solution of singular motion. To cope with the motion singularity problem discussed above, we have designed 5 degrees tilted caterpillar-based robot where each caterpillar is tilted 5 degrees with respect to the robot body frame as shown in Fig. 17 instead of straight caterpillars. The tilted caterpillar performs equally well in comparison to the straight caterpillar in no motion singularity condition as well as it aids the functionality to overcome motion singularity problem whenever needed. In motion singularity conditions, the tilted caterpillar provides the functionality to self-adjust the robot position in the pipeline bends so that three or more of caterpillars can eventually get in contact to the surface as depicted in Fig. 18. This can be achieved from the spiral motion provided by the tilted caterpillars. From the mechanical test, we proved the concept of self-adjustability on how the 5 degrees tilted robot self-adjust to a successful position from an unsuccessful position in a T-branch of the pipeline.

VII. Conclusion

In this paper, we dealt with the design concept and motion planning of a straight caterpillar-based fully autonomous mobile pipeline exploration robot that can be used for the inspection of 150mm pipelines. We conducted the thorough experiments to validate the motion planning mechanism of the robot for the excellent mobility in vertical as well as horizontal highly-bent pipelines. To overcome the singular motion conditions of the robot in T-branch, we proposed the concept of a 5 degrees tilted caterpillar design that exhibits self-adjusting capability. In the experiments, the pipeline exploration robot has shown good mobility using its wide straight wall-press caterpillars and its modular architecture. We plan to report quantitative results in the near future. We also plan to study in detail the motion planning mechanism and performance of the tilted caterpillar wheel-based robot as a future research.

References

[1] M. Muramatsu, N. Namiki, R. Koyama, and Y. Suga, "Autonomous mobile robot in pipe for piping operations," in *IROS*, vol. 3, 2000, pp. 2166–2171.

[2] S.-G. Roh and H. R. Choi, "Differential-drive in-pipe robot for moving inside urban gas pipelines," *Robotics, IEEE Transactions on*, vol. 21, no. 1, pp. 1–17, Feb. 2005.

[3] S. Hirose, H. Ohno, T. Mitsui, and K. Suyama, "Design of in-pipe inspection vehicles for ϕ25, ϕ50, ϕ150 pipes," in *ICRA*, vol. 3, 1999, pp. 2309–2314.

[4] C. Jun, Z. Deng, and S. Jiang, "Study of locomotion control characteristics for six wheels driven in-pipe robot," in *ROBIO*, 2004, pp. 119–124.

[5] J. Tao, Q. Peiwen, and T. Zhengsu, "Development of magnetic flux leakage pipe inspection robot using hall sensors," in *MHS*, 2004, pp. 325–329.

[6] M. Horodinca, I. Doroftei, E. Mignon, and A. Preumont, "A simple architecture for in-pipe inspection robots," in *Int. Colloquium on Mobile and Autonomous Systems*, 2002.

[7] Y. S. Kwon, H. Lim, E.-J. Jung, and B.-J. Yi, "Design and motion planning of a two-moduled indoor pipeline inspection robot," in *ICRA*, 2008, pp. 3998–4004.

[8] J. Y. Choi, H. Lim, and B.-J. Yi, "Semi-automatic pipeline inspection robot systems," in *SICE-ICASE*, 2006, pp. 2266–2269.

[9] A. Nassiraei, Y. Kawamura, A. Ahrary, Y. Mikuriya, and K. Ishii, "Concept and design of a fully autonomous sewer pipe inspection mobile robot "KANTARO"," in *ICRA*, 2007, pp. 136–143.

[10] E. Rome, J. Hertzberg, F. Kirchner, U. Licht, and T. Christaller, "Towards autonomous sewer robots: the MAKRO project," *Urban Water*, vol. 1, no. 1, pp. 57 – 70, 1999.

[11] J.-H. Kim, "Design of a fully autonomous mobile pipeline exploration robot (FAMPER)," Master's thesis, Louisiana State University, 2008.

[12] J.-H. Kim, G. Sharma, and S. S. Iyengar, "FAMPER: A fully autonomous mobile robot for pipeline exploration," in *IEEE-ICIT*, 2010.

[13] [Online]. Available: http://www.youtube.com/watch?v=hOQRzphJ4JU