FAMPER: A Fully Autonomous Mobile Robot for Pipeline Exploration

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***Abstract*—Pipeline-based applications have become an integral part of life. However, knowing that the pipeline systems can be largely deployed in an inaccessible and hazardous environment, active monitoring and frequent inspection of the pipeline systems are highly expensive using the traditional maintenance systems. Robot agents have been considered as an attractive alternative. Although many different types of pipeline exploration robots have been proposed, they were suffered from various limitations. In this paper, we present the design and implementation of a single-moduled fully autonomous mobile pipeline exploration robot, called FAMPER, that can be used for the inspection of 150mm pipelines. This robot consists of four wall-press caterpillars 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 uniqueness of this paper is to show the opportunity of using 4 caterpillar configuration for superior performance in all types of complex networks of pipelines. The robot system has been developed and experimented in different pipeline layouts.**

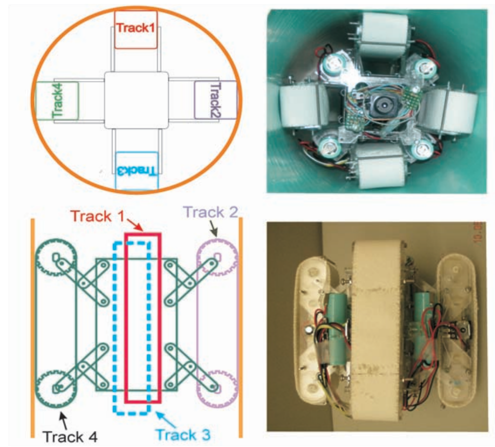

Fig. 1: The robot agent FAMPER

I. Introduction and Background

A number of robot systems for pipeline inspection has been developed in the literature. They were designed to detect and locate any leakage, damage, or corrosion in pipeline systems. Hirose et al. [3] proposed several types of robots for the inspection of pipelines ranging from Φ25, Φ50, up to Φ150 pipelines. Tao et al. [11] developed inspection robots for detecting defects inside the pipeline. Maramatsu et al. [8] and Roh and Choi [10] developed pipeline robots to pass through sharp curves inside underground pipelines. Jun et al. [5] studied six wheels driven in-pipe robot with the wheels fixed 60 degrees apart in its circumstance. Horodinca et al. [4] proposed pipeline inspection robots for Φ40 up to Φ170 mm pipelines.

Recently, Kwon et al. [7] proposed a reconfigurable pipeline inspection robot for inspecting 80∼100mm pipelines, which works from the collaboration of two separate modules connected by a compression string. Moreover, while a huge number of robot based systems have been proposed are manually controlled, a few have considered semi-autonomous/autonomous solutions. Choi et al. [1] introduced a semi-automotive pipeline inspection robot for small sized pipelines. KANTARO [9] is the prototype of a fully autonomous mobile robot designed for 200∼300mm sewer pipeline inspection. MAKRO [2] is also one of the prototypes of a fully autonomous, untethered, multi-segmented, self-steering articulated robot which has been designed for autonomous navigation in 300∼600mm pipelines at dry weather conditions.

However, the previously proposed 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. In this paper, we propose a fully autonomous mobile robot for pipeline exploration, called FAMPER, that can be used for the inspection of 150mm pipelines. It consists of four wall-press caterpillars which are 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. In addition, the robot size is small; it is scalable; it has efficient steering capability; and it is cost effective. The robot system has been designed, implemented, and experimented in different pipeline layouts.

II. FAMPER Architecture

FAMPER consists of a main body, four caterpillar tracks, an extendable link system, and other attached functions as demonstrated in Figure 1. The attached functions composed of different sensing, communication, and actuation devices as per the pipeline inspection demands.

FAMPER has four essential features. The first and foremost feature is its mobility, which enables it to travel in any spatial conditions of the pipeline (e.g., horizontal and vertical) involving with any kind of pipeline fittings (T-branches, Y-branches,

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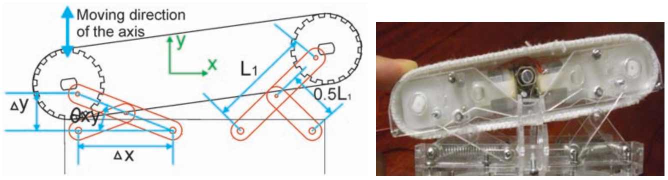
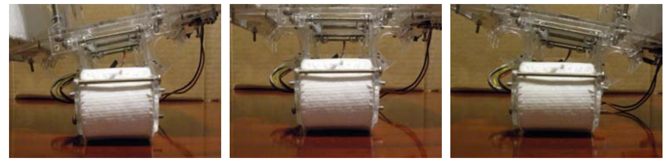


(a) Model of link mechanism (b) Feature of link mechanism

Fig. 2: Model and feature of FAMPER's link mechanism



(a) Left gradient track (b) Balanced track (c) Right gradient track

Fig. 3: Tilting mechanism of FAMPER's link system

and elbows), using its caterpillars and extendable link system. Secondly, the operational architecture used is very simple, flexible and adaptable enough for the inspection environment being considered. Thirdly, it has flexible extension interface for physical actions which enables it to integrate various different mechanical and chemical devices, such as robotic arms or chemical sprayers. Lastly, it is comprised of a powerful tracking system for handling navigational complications both efficiently as well as autonomously.

A. Caterpillar Configuration

The caterpillar wheel is made of two motors, a rotary encoder, and a wrapping belt as shown in Figure 1 and 2b. Each caterpillar track is arranged 90 degrees apart. 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 by differentiating the speeds of the four caterpillars. In the caterpillar mechanism used in FAMPER, the distance between the central body and the caterpillar tracks can be determined based on the movement of the flexible links, the elastic restoration force on the spring at the each suspension link, and reaction forces from the wall. For the caterpillar mechanism shown in Figure 2a, the height of the track from the central body can be deduced using the Pythagoras theorem using Equation 2, where L_1 is the length of the link connecting the caterpillar track and the main body (also called crank), Δx and Δy are the displacements along the x- and y-axes respectively, and θ_{xy} is the suspension angle between the crank and the central body of the robot. The another link of length $0.5L_1$ connects the midpoint of the crank to the central body. Moreover, the vertical displacement Δy of the caterpillar track from the central body can be calculated using the Equation 1 involving the horizontal displacement Δx.

$$tan(\theta_{xy}) = \frac{\Delta y}{\Delta x} \Rightarrow \Delta y = \Delta x \; tan(\theta_{xy}) \tag{1}$$

Again, from pythagoras theorem

$$L_1^2 = \Delta y^2 + \Delta x^2 \tag{2}$$

$$\text{which gives, } \Delta y^2 = L_1^2 - \Delta x^2$$

$$\text{hence, } \Delta y = \sqrt{L_1^2 - \Delta x^2}. \tag{3}$$

The force with which the caterpillars press the inner surface of the pipeline can be determined by adjusting the stiffness of the spring. FAMPER's adaptable tracks and suspensions provide sustainable performance in uncertain pipeline conditions as well as sufficient traction forces during movements. In addition, FAMPER can be equipped with the capability of having suspension independent of other modules. When a track meets some kind of obstacles, it has the ability to be tilted for increasing its contact surface as shown in Figure 3. This feature of having flexible tracks increases the gripping force of the track, which is very important for moving through damaged pipelines and obstacles.

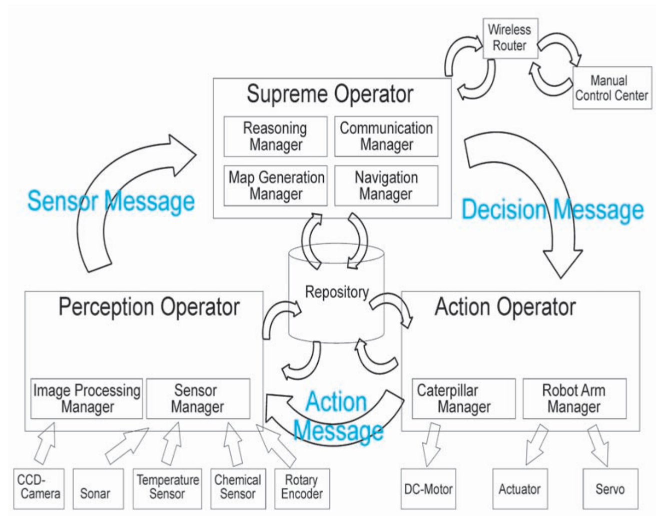


Fig. 4: Flow diagram of FAMPER's operational architecture

B. Operational Architecture

FAMPER's operational architecture consists of three operator modules: (a) Supreme Operator (SO); (b) Perception Operator (PO); and (c) Action Operator (AO) as given in Figure 4. 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 FAMPER's architecture enables each module to be developed and extended independently (for instance, the AO only depends on the property values that are defined for it). These property values can be changed by SO or PO depending on the environmental conditions or the changes that any other operator might require for performing that action.

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 that feedback. For example, when PO senses 90 degrees branch and sends sensed message to the Navigating Manager (NM) at SO, SO makes the decision to turn 90 degrees and NM sends back the decision message to the Caterpillar Manager (CM) at AO. (for instance "turn 90 degrees" message instead of each motor speed value). After receiving the message, CM reads available properties about 90 degrees turn and controls the DC motors at caterpillars using different speed values.

When the action event is started, CM sends the action message to PO. PO then observes changes and sends the observed results to SO within monitoring action property value in central repository. SO, then, tunes properties of AO based on the sensed message which acts as a feedback for the decision to be taken. The central repository contains properties of operators and managers, predefined rules, sensed data, map information, results of actions, and history of events. The detailed description of the operational architecture is given in [6].

C. Control Structure

FAMPER turns at elbows and branches using its four independent caterpillar tracks. With independently controlling the speed and rotating direction of caterpillars, FAMPER can perform very sophisticated turning operations in any three dimensional pipeline layout. Figure 5 illustrates motor speeds for all four caterpillars depending on the direction in which the robot is intended to turn. For example, FAMPER wants to move forward in a straight pipeline, all tracks rotate in same direction with equal speed but when it wants to turn 90 degrees, CM sets the motor speed of track 1 to 0 and motor speed of tracks 2, 3, and 4 to 10 based on the property values provided in Figure 5. FAMPER 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.

D. Electrical Instrumentation

The electrical architecture of FAMPER 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. Although Gumstix is a small yet powerful motherboard, it does not include all the additional modules that are needed for communication. We integrated some expansion boards with the required communication, sensing, and reaction capabilities; some of which we used in FAMPER are WIFI-Stix and Robostix. Nevertheless, because of its minute size and high processing power, it can be used in micro-sized devices. The designed applications can take advantage of its processing power by using high level languages like Java or Python, instead of programming in low level languages such as assembly language or PBASIC.

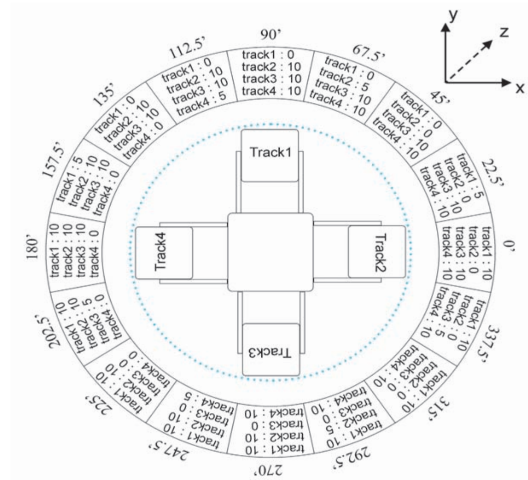


Fig. 5: Modes of FAMPER's operation

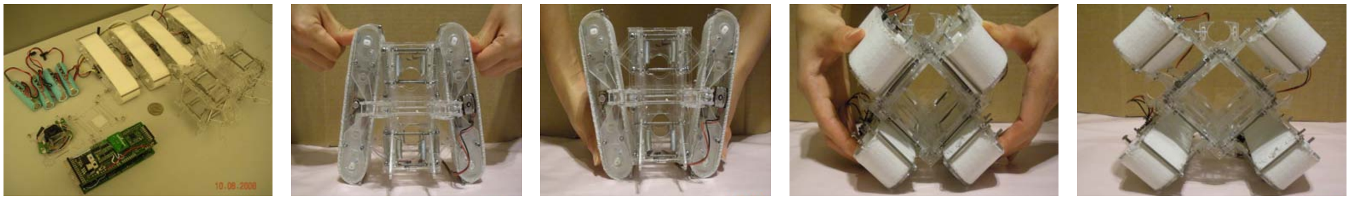
Different sensing and controlling functions are also implemented in FAMPER to make it fully autonomous and mobile in pipeline inspection and exploration. A compass can be used for obtaining the direction in which the robot is heading, a 3D accelerometer can be used to get the tilt information of the robot, and a rotary encoder can be used to calculate the distance the robot traveled so far. The sonar can be used to determine the obstacle or hole position in the pipeline. The electrical architecture implemented in FAMPER is given in Figure 7 and will discuss in detail at Section III-B.

III. Experimental Implementation

The length of the robot is 148mm and the exterior diameter is 127mm at maximum shrinking condition and 157mm at normal condition. The main body consists of the Gumstix board extended by inserting some expansion boards with the required communication, sensing, and reaction capabilities. The interface board provide the interface to the micro-controller, compass, 3D-accelerometer, rotary encoder, and Li-ion battery.

A. Mechanical Platform

This particular implementation of FAMPER focuses on verification of mobility in complex pipeline layouts consisting of different pipeline bends, and vertical and horizontal geo-spatial conditions with manual controlling system based on FAMPER's operational architecture using Gumstix-based devices. FAMPER is implemented as a caterpillar-based wall-press robot for the efficient navigation and inspection of 150mm pipelines. It has implemented four caterpillar tracks each of which are 33mm wide and 148mm in length. Each



(a) Disassembly of FAMPER (b) Up side pressing scenario (c) Down side pressing scenario (d) Whole body pressing scenario (e) No pressing scenario

Fig. 6: FAMPER's disassembly and features of links and suspensions

caterpillar track is equipped with a rotary encoder to calculate the distance moved so far. For giving enough torque for efficient rotation, each caterpillar track has two motors attached one on each side of the track. The driving power is transmitted to the caterpillar by a set of two geared motors, two pulleys, and a belt as shown in Figure 6.

Along with the caterpillar system, the wall-pressing mechanism is developed to make FAMPER climb up and down in the vertical situations as well. To achieve efficient wall-pressing mechanism, each caterpillar track is mounted to the central body using four independent suspension links. These links are responsible for giving the required gripping force to the robot; the robot can be contracted from 157mm to 127mm using these links as given in Figure 6. The suspension link's ability to contract and expand make the FAMPER flexible enough to move through the highly-bended pipelines as well. The central body frame of FAMPER is of 40mm X 40mm X 108mm size as shown in Figure 8d, 8e.

B. Electrical and electronic Platform

FAMPER's small and powerful computing system is sandwiched between the two interface boards, which are interconnected to all the internal ports of the Gumstix, Robostix, sensors, and external controllers as demonstrated in Figure 7. The power for all the internal boards is also regulated by the bottom and top interface boards. This layout gives easy and universal access to all the ports available in front and rear part of the central body. The computing system consists of a stack of 5 boards, which are bottom interface board, Robostix, Gumstix, Wifi-stix and top interface board as shown in Figure 8a, 8b, and 8c from bottom to top respectively.

FAMPER has attached RF-CCD Camera which can send the video stream independently without any intervention from other modules. The sensors, which are included in this particular implementation of FAMPER, are a 3D-accelerometer, a compass, and a rotary encoder. The 3D-accelerometer is to determine tilting information of the robot, the compass for accessing the direction on which the robot is heading, and the rotary encoder to calculate the distance traveled by the robot so far. 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

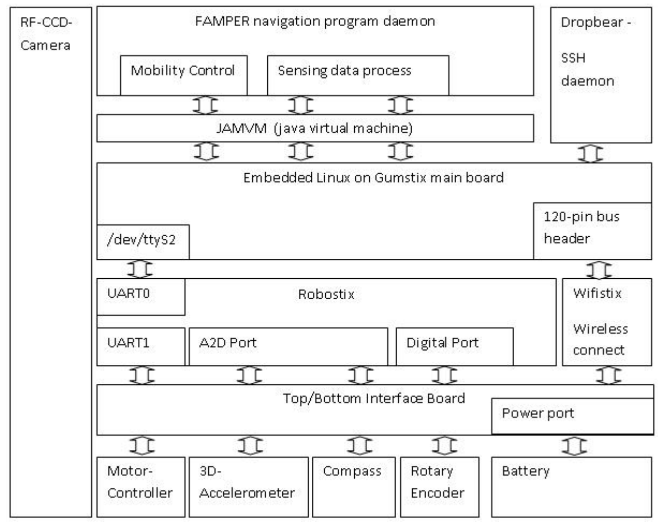


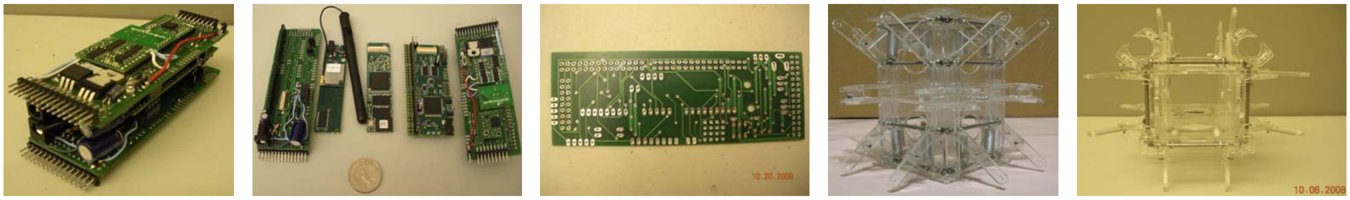
Fig. 7: Block diagram of implemented electrical architecture

with embedded Linux platform which has the capability of running programs written on high level languages. In this implementation we programmed the controlling interface of FAMPER using Java. The sensor readings have been read using programs written in AVR-C which are later ported to the Robostix.

C. Control Platform

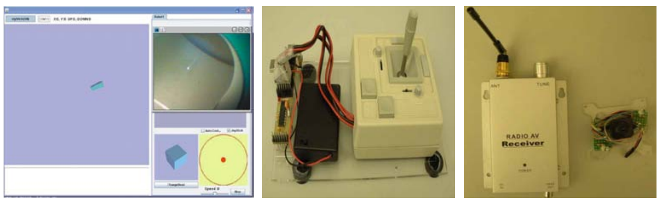
We have developed a Manual Control Program (MCP) which aids in operating FAMPER in different pipeline layouts. The program comprises of four major panels: (a) 3D view of FAMPER's position; (b) RF video panel to display video stream from RF camera; (c) Control Panel (CP) to control FAMPER using the FAMPER Controller (FC) and/or the GUI interface and to provide the tilting and direction of FAMPER as indicated in mini 3D view; and (d) Message Console (MC) to display the detailed status of FAMPER. The controlling signals are sent to the computer running the FAMPER's MCP using FC as given in Figure 9. FC uses an analog joystick and also provides flexibility of sending the control signals using Bluetooth and USB connections. It has been programmed using C for PIC (Programmable Intelligent Computer) micro-controller, PIC16LF88.

In order to control the FAMPER from a remote location, we used RF video system which is small in size, consumes low



(a) Main Board of FAMPER (b) Dissembly of main board (c) Interface board (d) Side view of body frame (e) Front view of body frame

Fig. 8: FAMPER's electrical dissembly and central body frame



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

Fig. 9: FAMPER controlling and RF video system

(a) Entering pipeline (b) Entering Elbow (c) Exiting pipeline

Fig. 10: Test bed of 45 degree elbow

(a) Entering pipe (b) Entering elbow (c) Exiting elbow (d) Exiting pipe

Fig. 11: Test bed of 90 degree elbow

(a) Entering pipe (b) Entering T-bend (c) Exiting right (d) Exiting left

Fig. 12: Test bed of T-branch

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. The RF video camera is completely independent from the FAMPER's main electrical system.

IV. Performance Evaluation

A. *Traveling through Different Pipeline Bends*

We experimented FAMPER in different pipeline layouts. First, the robot is evaluated in different pipeline bends (45 degree elbow, 90 degree elbow, T-branch, and Y-branch) separately. Later, we evaluated the robot in a complex pipeline layout consisting of all the aforementioned bends where it needs to perform both vertical and horizontal motion.

Figure 10 shows the FAMPER starts traveling in a straight pipeline in one side and turns 45 degrees to get back to the straight pipeline on the other side of the elbow. Figure 11 shows the robot turns 90 degrees to get back to the other side. In both of the bends, by changing the direction of the motors, it can go backward by following the previous path. Figure 12 shows the robot is turning to different directions in a T-branch of the pipeline. Similarly, the robot travels in Y-branch of the pipeline by taking the path as shown in Figure 13.

The robot is also 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. The performance of FAMPER in one of such layout is given in Figure 14. FAMPER manages to travel through these layouts by changing the motor speed appropriately.

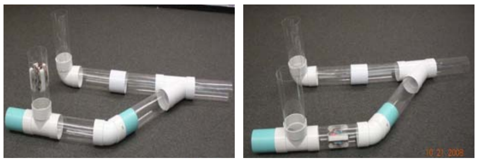
B. *Performance Results*

FAMPER is evaluated for its performance in crossing a straight pipeline from one end to the other at different inclination angles to see how would the speed be affected with the inclination angles. Apparently, as the inclination angle increases from 0 degree to 90 degrees, the time taken by FAMPER to reach the other end decreases for the downhill case, however, increases significantly for the uphill case as depicted in Figure 15.

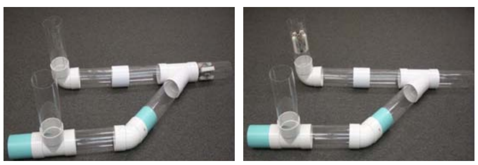
In addition, we have compared the FAMPER's performance in crossing different types of elbows from one end to the other end via the elbow. All the pipelines considered for this experiment are of same length. As we can notice from Figure 16, the time taken for completing the trip from one end to the other increases with increasing bending angle because, in elbows with different bending angles, FAMPER has to adjust the motors speed in different ways, as mentioned earlier,

(a) Entering pipe (b) Entering Y-bend (c) Exiting right (d) Exiting left

Fig. 13: Test bed of Y-branch

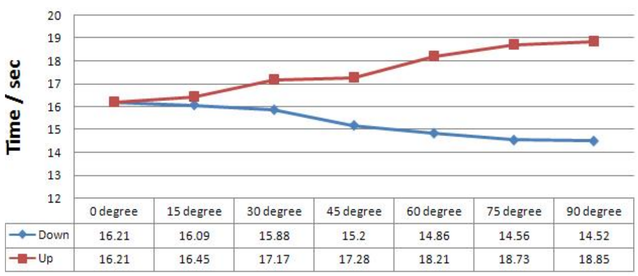


(a) Entering pipe (b) Exiting T-bend



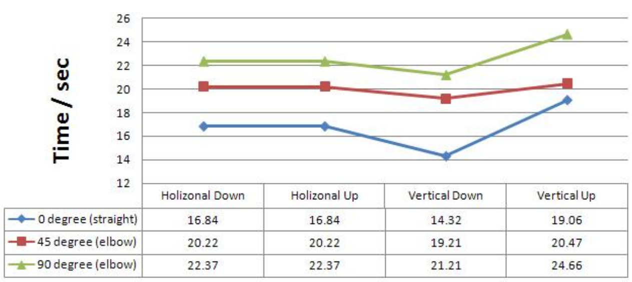
(c) Exiting right (d) Exiting left

Fig. 14: Test bed of complex pipeline layout



	0 degree	15 degree	30 degree	45 degree	60 degree	75 degree	90 degree
Down	16.21	16.09	15.88	15.2	14.86	14.56	14.52
Up	16.21	16.45	17.17	17.28	18.21	18.73	18.85

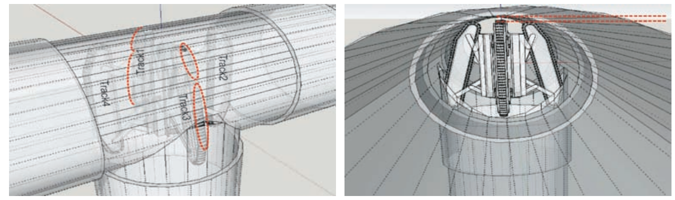
Fig. 15: Inclination angle vs. time for straight pipeline of 4 feet length



	Holizonal Down	Holizonal Up	Vertical Down	Vertical Up
0 degree (straight)	16.84	16.84	14.32	19.06
45 degree (elbow)	20.22	20.22	19.21	20.47
90 degree (elbow)	22.37	22.37	21.21	24.66

Fig. 16: Performance changes with different elbows in pipeline of 4 feet length

in order to successfully pass through the elbow. Moreover, the horizontal and vertical conditions behave in a similar way we mentioned in the previous experiment. In summary, the experimental results show that FAMPER can effectively navigate through most of the pipeline bends involving both horizontal and vertical motion.



(a) Singular motion (b) Inside view

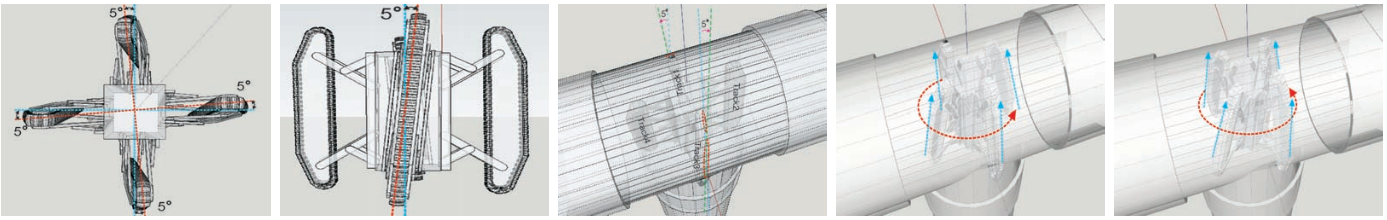
Fig. 17: Motion singularity problem

V. Motion Singularity Problem and Proposed Solutions

We performed experiments to check motion capability at elbows, T-, and Y-branches. The experimental environment is the same pipeline layout given in Figure 14. The “motion singularity” problem [7] has been observed for some of the cases while FAMPER was passing through T-, and Y-branches because the robot looses contacts at turning positions as shown in Figure 17. One can also notice that such cases are relatively few for the four caterpillar based robots than those of three caterpillar based robots [7]. We have learnt that FAMPER can be able to turn in all pipeline layouts when at least three caterpillars manage to be in contact with the pipeline surface as illustrated in Figure 18. However, there are also some cases where only two caterpillars can contact the pipeline surface. In those cases, it can turn in all possible configurations except only two caterpillars in the diagonal are in contact with pipeline surface as previously mentioned in Figure 17. Nevertheless, 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-, or Y-branches. However, the straight caterpillar mechanism cannot provide self-adjust capability.

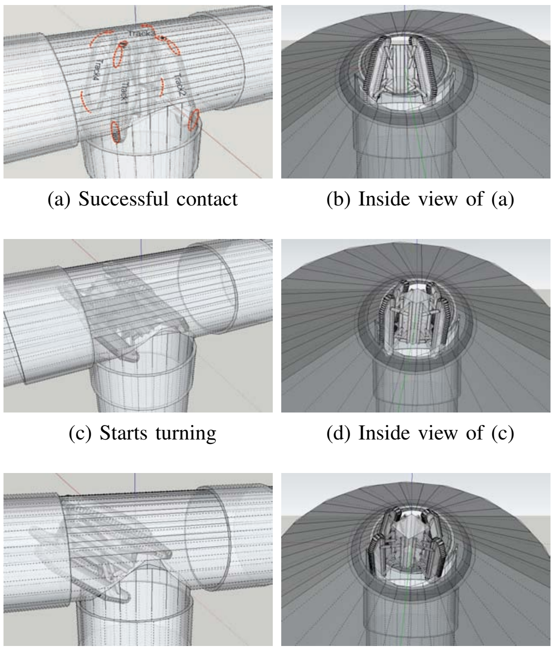
To overcome motion singularity problem, we have designed two types of caterpillar mechanism. First, we propose 5 degrees tilted caterpillar design with respect to the robot body frame as shown in Figure 19a, 19b instead of straight caterpillars. The tilted caterpillar performs equally well in comparison 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 position so that three or more of caterpillars eventually get in contact to the surface as depicted in Figure 19c, 19d, 19e. This can be achieved from the spiral motion provided by the tilted caterpillars.

Second, we designed a bendable caterpillar mechanism to retain needed pipeline surface contact for the robot to successfully turn in bends as depicted in Figure 20. The bendable caterpillar is segmented to three parts: front, middle, and end frame. The front and end frame link to middle frame in each side, can be bendable by maximum of 60 degrees and have 30 degrees fork which enhances flexibility in turning and crossing obstacles. The middle frame has four shrinkable



(a) Tilted front view (b) Tilted side view (c) Starts self-adjusting (d) Self-adjusting (e) At turning position

Fig. 19: Tilted caterpillar design to overcome motion singularity



(a) Successful contact (b) Inside view of (a)

(c) Starts turning (d) Inside view of (c)

(e) Finished turning (f) Inside view of (e)

Fig. 18: Successful motion at T-branch

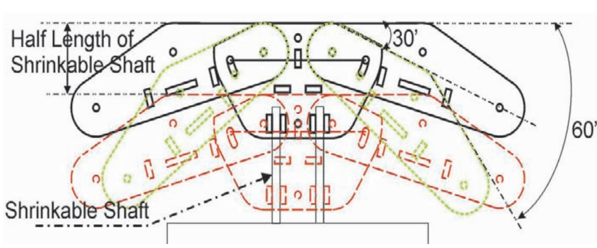


Fig. 20: Bendable caterpillar design to overcome motion singularity

shafts which provide support for the caterpillar frame. The caterpillar frame is also shrinkable by 50% the length of its shrinkable caterpillar shaft, giving the robot the flexibility to use in inspecting pipelines of variable sizes. For example, if total length of the shaft is 40mm, caterpillar frame can be shrinkable by 20mm in maximum. Those shrinkable and bendable frames enable the robot agent to travel vertically as well as horizontally in pipelines with different fittings.

VI. Conclusion

This paper proposed a fully autonomous mobile robot for pipeline exploration, called FAMPER, that can be used for the inspection of 150mm pipelines. We have also described the mechanism that FAMPER provides for the excellent mobility in vertical as well as horizontal pipelines, and proposed the system architecture that would enable FAMPER to be fully autonomous. FAMPER is equipped with a small yet powerful computing system which makes it extendable for more complicated tasks and provides easily extendable interfaces for various sensing and actuating devices. In the experiments, FAMPER showed outstanding mobility in 150mm sewer pipeline layout. The more detailed analysis of control algorithms for full autonomy remains as a future work.

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