Robotic System with Power Line Communication for In-pipe Inspection of Underground Urban Gas Pipeline

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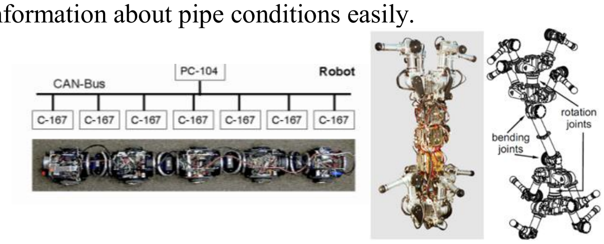
***Abstract*—As natural gas gains more and more popularity, the security of related infrastructure such as pipelines has been a hot topic in society. Even though NDE (Non-Destructive Evaluation) technology is developing rapidly, how to inspect pipelines buried underground effectively is still a problem remaining unsolved. The reason is that there is no developed equipment which can pass through pipelines carrying NDE sensors and provide the circumstances under which testing tasks can be done properly. This paper designs a practical robotic system called "Inspector" for in-pipe inspection of underground urban gas pipelines using PLC, which stands for power line communication. Inspector is able to pass through different obstacles (bends, elbows and tees) at a pipe network, climb in vertical pipes and recover from capsizing. Except for that, the robot can also conduct inspection tasks and show conditions of pipes clearly. Besides, this paper proposes a self-control strategy using laser range finders, which are used to detect road conditions ahead of Inspector. With the efforts of all the team members, a prototype of the robot system has been completed, qualified with the functions mentioned above.**

Keywords-robotic system; in-pipe inspection; power line communication

I. Introduction

Natural gas has become one of the most important sources of energy in the past few years [1], [2]. As a result, there are a great number of gas pipelines underground for gas transmission. Because of long service time, corrosion or physical pressure, some pipes are in a bad condition [3]–[6]. Faulty pipes tend to leak gas, which is a big threat to the people around. However, due to the complex underground environment and high risks of inspecting when pipes are still working, there are few ways to do the job. The traditional means of inspection using PIG, which stands for Pipeline Inspection Gauge, cannot meet the demand because of its inability of self-driven. PIG is only driven by the gas or oil pressure in pipes [7]–[9]. However, the gas pressure in urban gas pipelines is not big enough to drive PIG. Self-driven robots are equipped with more flexibility and adaptability, which are important to deal with different situations in pipes. Equipped with NDE sensors, this kind of robots can also get information about pipe conditions easily.



MAKRO MORITZ

Figure 1. MAKRO and MORITZ inspection robot

There has been some research in this filed [10]–[18]. But most of existing robotic systems fall short of practicality and simplicity. For instance, Bernhard Klaassen from Germany has designed a multi-joint robot for sewer inspection-MAKRO (Fig. 1) [19]–[21]. However, MAKRO does not have effective ways to overcome its gravity, so it can only be used in flat or slightly sloped pipes. More often than not, inclined and vertical pipes appear frequently when inspecting pipes. Andreas Zagler from Technical University of Munich has also devised a pipe inspection robot called MORITZ (Fig. 1) [22]. The robot has so many degrees of freedom that it is hard to be controlled the robot precisely and keep its balance.

This project has been conceived and designed to do in-pipe inspection in an easier and more liable way. To increase flexibility, the robot is designed modularly. In the system, wiring is simplified using PLC (power line communication). In this case, signal transmission and electricity supply are completed through the same wires. In addition, Inspector is capable of passing through straight pipe segments, bends, elbows and tees. Proceeding in vertical pipelines is also a

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breeze to Inspector because it has support modules to keep from falling down. Besides, Inspector allows customizing. Engineers can change Inspector by reorganizing different modules. On top of that, we also come up with a self-control strategy with laser range finders. In order to control Inspector and show pipes' conditions clearly, a specific software is developed to build a bridge between Inspector and users.

In this paper, we present the entire design process of Inspector. In the following section, the structures of different modules are illustrated, including locomotion module, guidance module and NDE sensing module. Then, a control system based on PLC and STM32 (MCU) is introduced.

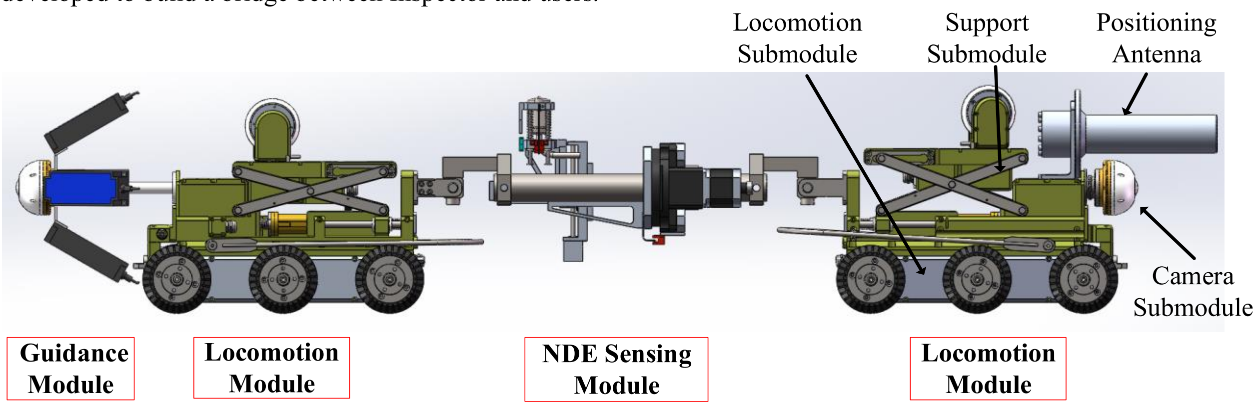

Figure 2. Overall design configuration for Inspector

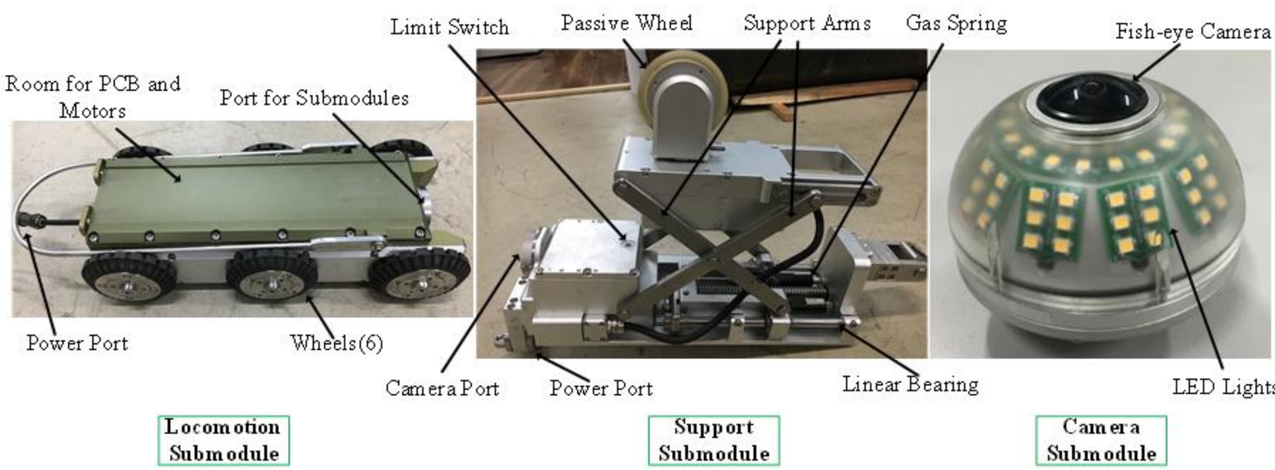

Figure 3. Locomotion, Support and Camera Submodules

After that, a user interface is also shown in the third section. The fourth section is about experiments designed to check if Inspector can work well in different scenarios. Finally, this paper is concluded and future work is depicted.

II. STRUCTURE DESIGN

A. Overall Configuration

The overall segmented design of Inspector is depicted in Fig. 2. Modular design is applied in the creation of Inspector to strengthen its reconfigurability and flexibility. Inspector is mainly composed of a guidance module, two locomotion modules and a NDE sensing module. A locomotion module includes support submodule, camera submodule, locomotion submodule and positioning antenna. Due to the guidance module, the front locomotion module is not equipped with camera submodule and positioning antenna. The structures of the submodules are depicted in Fig. 3

B. System Design: by Subsystem

1) Locomotion module

a) Locomotion submodule

Locomotion submodule is actually like a car with six wheels mounted by two rows. Each side of the submodule has three wheels synchronously driven by one motor. The two rows of wheels can proceed at different speeds. Consequently, Inspector has the ability to change proceeding direction by changing the speeds of both sides respectively. And the three wheels on each side keep Inspector steady. If there are only two wheels on each side, Inspector tends to tilt because of the falling of one or two wheels when passing tees. More wheels mean more support points but more complexity. Three wheels on each side are enough for in-pipe inspection robot to handle the scenario.

b) Support submodule

This module is mainly used for supporting robot in tilted or vertical pipes. In order to climb up in such pipes, a pair of support arms are used to lift a passive wheel to support Inspector. With the gas spring and the stepper motor chosen properly, Inspector could work in slopped pipes with sufficient friction force. The limit switch is for limiting the stroke of the support arms.

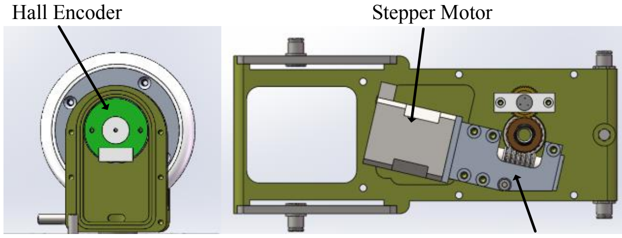

Figure 4. Passive wheel design

In addition, since the wheel on the top is passive, it can also be used to count the distance Inspector has proceeded precisely. Therefore, we put a Hall encoder on one side of the passive wheel to count the rotation number of the wheel (Fig. 4). The data can help to locate Inspector. Besides, the orientation of the passive wheel can be controlled by a stepper motor and the gearbox under it (Fig. 4). This feature offers an effective way to address the problem of capsizing (more details shown in the 4th section).

c) Camera submodule

In this project, considering enlarging the range of observation, we choose the fish-eye camera. An array of LED is arranged around the camera in the front of the module to supply lights. The brightness of the LED can be controlled by operators.

d) Positioning antenna

This device can launch ultra-low frequency electromagnetic waves, which are qualified with great ability of penetration. When Inspector is working underground, the control station on the ground receive the signal and locate the robot.

2) Guidance module and self-control strategy

Guidance module mainly contains four laser range finders and a fish-eye camera (Fig. 5). This module is mounted in the front of Inspector and its central axis coincides with the axis of pipes.

The laser range finders detect the distances between the head of Inspector and the inner surface of pipes in four directions. When a bend or a tee shows in front of Inspector, the distances detected change differently (Fig. 6). The changing patterns of the distances demonstrate the condition of pipes in front and also provide the data to calculate the distance between Inspector and roadblocks, the radius of bends or the size of tees. Through analyzing the data with the robot's speed, Inspector can also know when and where to take proper actions to avoid being stuck in pipes. It is the fundamental function which contributes to the automation of Inspector.

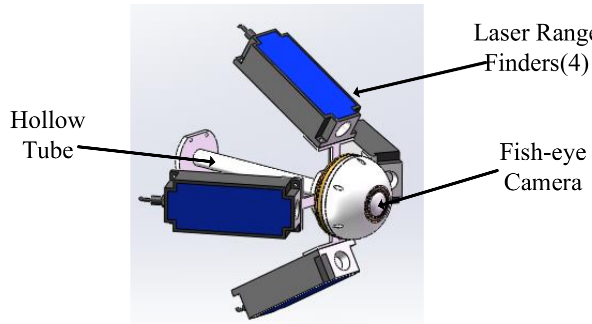

Figure 5. Passive wheel design

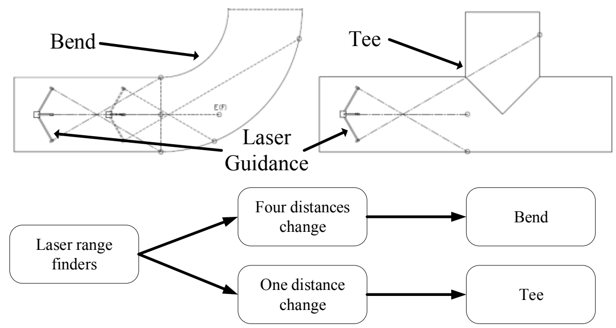

Figure 6. The detection principle of bends and tees

3) NDE sensing module

Fig. 7 shows the structure of the NDE sensing module. There are a lot of non-destructive testing methods, most of which need some special probes to conduct tasks. This module is designed to adapt to various probes and control the testing process.

In this module, there are three stepper motors, including rotate motor, scan motor and lift motor. Rotate motor enables probe and the related components to rotate around the hollow tube. Scan motor is used for moving a probe along the hollow tube, while lift motor controls the movement vertical to the hollow tube. The probe can test a cylindrical surface each time. The positioning switches are used to control the maximum stroke of execution parts and record the reset point.

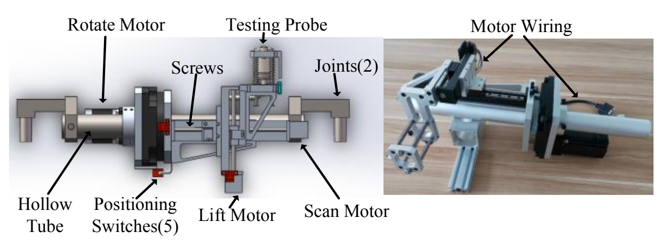

Figure 7. Design of NDE sensing module

III. Control System Design and User Interface

A. Control System

The electronics architecture implemented for Inspector is based on a distributed architecture (Fig. 8). Using PLC, signals and electricity can be transmitted through the same wires. A PLC master is set outside of pipes, which connects with the control center through Ethernet.

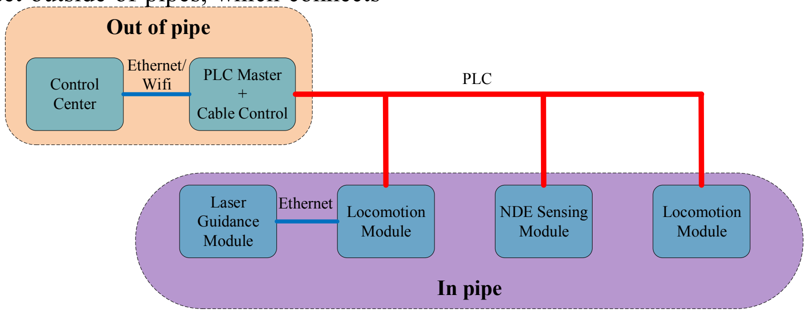

Figure 8. Distributed electronics architecture

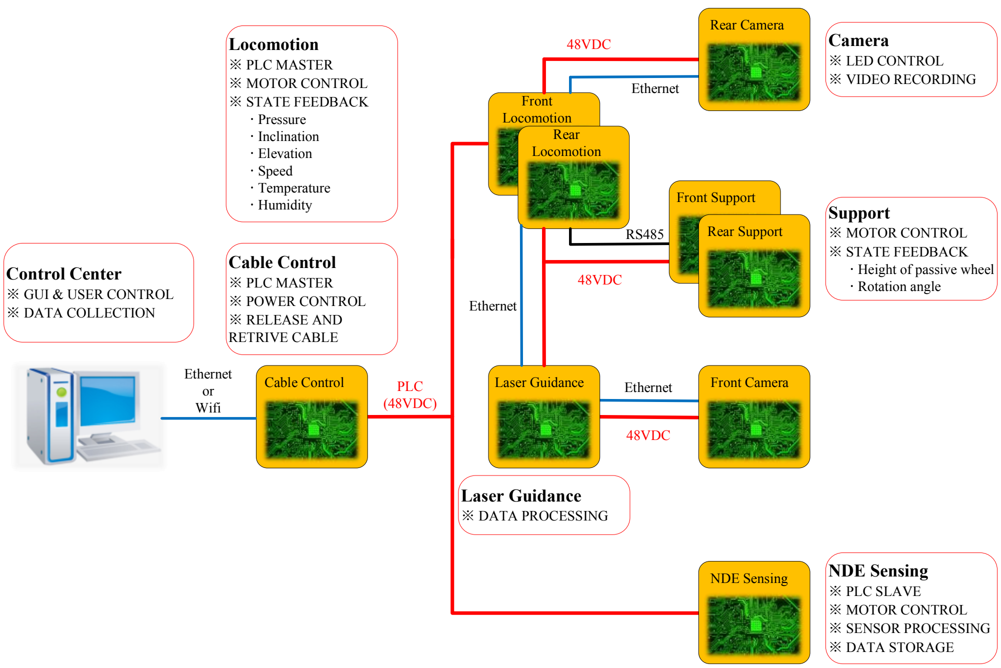

Figure 9. Functional distribution across robot's processor and interconnecting power (dc) and data communication

Both of locomotion module and NDE sensing module have PLC slaves while guidance module communicating with the front locomotion module through Ethernet. PLC devices connect with each other through power wires. In each module, there are one or more control PCBs based on STM32 chips (32bit). In this project, we mainly use STM32F407VGT6 and STM32F103CBT6. Various communication ports, good performance and low power consumption make STM32 become one of the top choices in this project. Fig. 9 shows the functional distribution across Inspector's processor, interconnecting power (dc) and data communication.

B. *User Interface*

To control Inspector conveniently and show data clearly, a software has been developed using C#, which is shown in Fig. 10. In order to build the connection between the control center and Inspector, power panel (1) and Ethernet setting (2) should be set up first, including turning on the power switch, connecting the clutch for the cable, choosing the mode of control and connecting Ethernet. The setting panel (2) also includes a general setting, the switches for taking photos and recording videos. The cable can be released or retrieved automatically according to the locomotion of Inspector. Various control modes allow the two locomotion modules to be controlled synchronously or respectively. The control panels (3 and 4) can help define the speed and the direction of Inspector, change the brightness of LEDs and control the passive wheel. In the middle of the interface, all sorts of state parameters are shown (5), which help to know whether everything goes well in pipes. The real-time video images (6 and 7) show the front and the rear fish-eye views of the cameras.

IV. Simulations and Experiments

A. *Motion Simulation*

To exam the feasibility of the whole design, we build a three-dimension model and conduct some simulations, which include passing through 90-degree bends and tees and recover from capsizing. The pipe's diameter is 400mm and the speed of Inspector is 0.5m/s. The simulation result shows that Inspector can pass through these pipes smoothly. According to the analysis, Inspector goes through bends (Fig. 11) and tees (Fig. 12) at a constant speed and the inclination is limited in an acceptable range. When passing tees, there is only one wheel of the locomotion module hanging in the air. In this case, the locomotion module can keep balance without inclination.

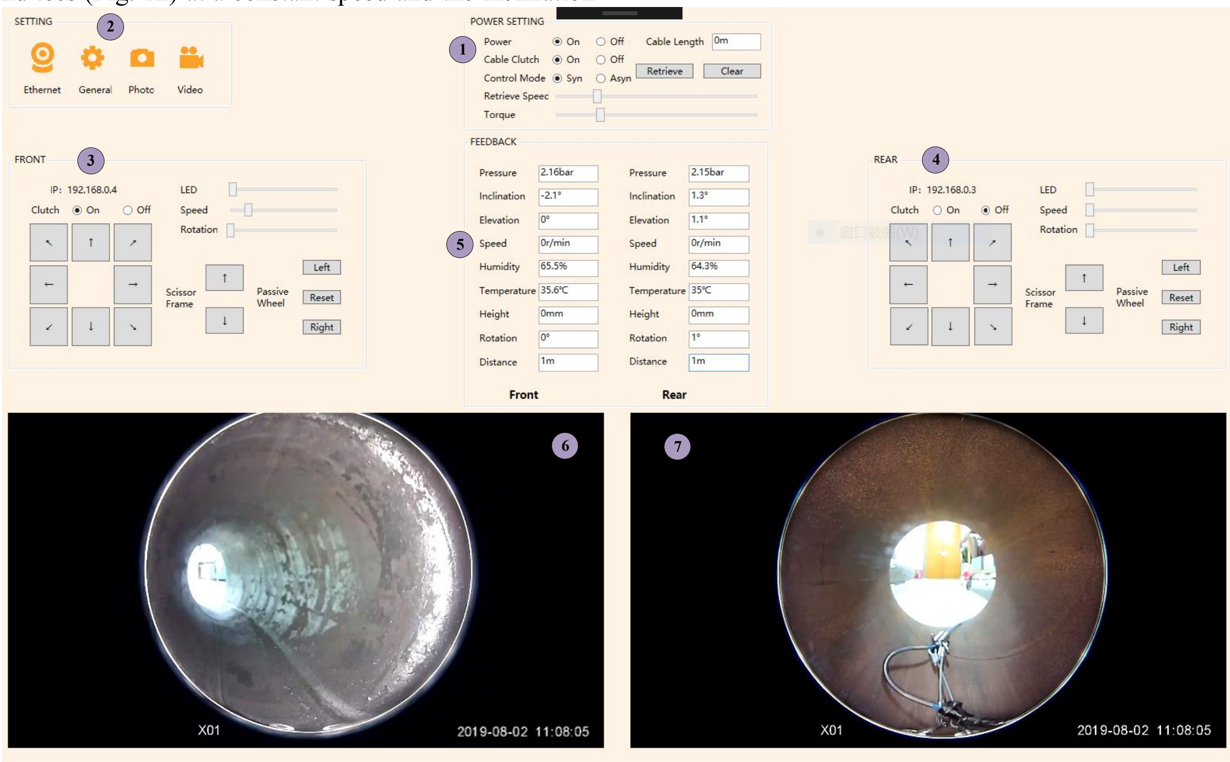

Figure 10. GUI depicting video windows, settings and feedback

However, even if an elaborate design is made to avoid inclination, there is no guarantee that capsizes would not happen. So the capability of returning back to the normal state is important for Inspector. Fig. 14 illustrates how Inspector recovers from the abnormality. The process has two phases (A→B and B→C). At A, Inspector is in inclination and one row of wheels are hanging in the air. From A to B, the passive wheel rotates a certain angle and lift the support arms up gradually to keep friction force while Inspector is proceeding forward. In this case, the inclination of Inspector reduces progressively and reach B after a short distance. Then, the passive wheel is reset. From B to C, because none of the wheels is hanging in the air, Inspector can go back to its normal position through controlling the bottom wheels to change Inspector's direction. After going forward for a short distance, Inspector reaches C finally. The blue line shows the track of the passive wheel in this process.

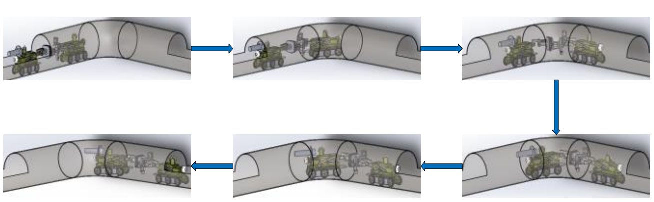

Figure 11. Process of passing 90-degree bend

Figure 12. Process of passing tee

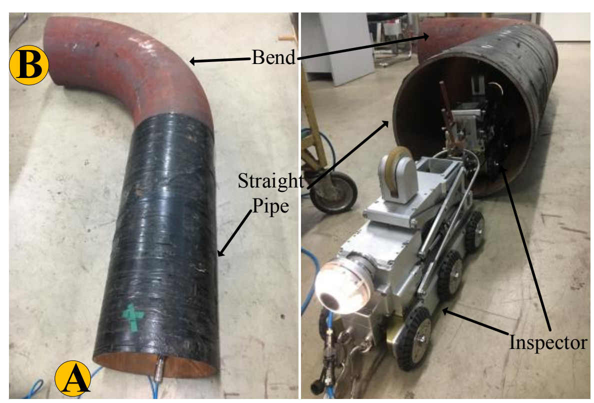

Figure 13. Experiment environment

B. *Experiments*

All the experimental processes are depicted in Fig. 15.

1) *Pass through bends*

The experimental pipe contains a short straight pipe and a bend (Fig. 13). Inspector enters the pipe at A and comes out from B. The process is depicted in Fig. 15. The experiment shows Inspector can pass through bends successfully. Its results are consistent with the simulation.

2) Climb in a vertical pipe

In this experiment, we put Inspector into a vertical pipe. Then, the support arms are extended to the most. The result shows that Inspector can climb up in a vertical pipe. And each locomotion module is able to carry extra weight up to 5kg, which can be bigger if the gas springs are enhanced.

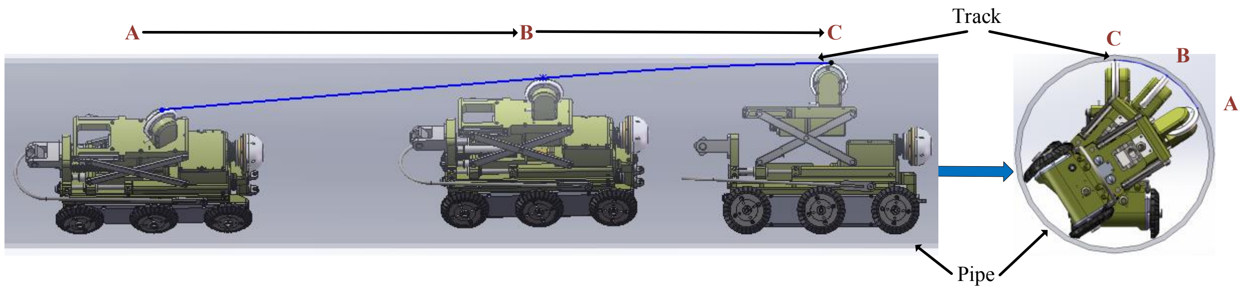

Figure 14. Process of recovery from capsizing

Figure 15. Experiment processes

3) Recover from capsizing

For an in-pipe inspection robot, capsizing can be destructive if the device is not capable to recover from abnormal positions. In this project, we solve the problem using the passive wheel.

In the process, Inspector leans against the pipe while the left row of wheels hangs in the air at A. Then, the passive wheel turns left for a certain angle. The support arms extend while Inspector moving forward at the same time. During the process, the inclination declines and the hanging wheels get close to the pipe and reach B after a while. After the inclination remains unchanged for a short time, Inspector turns right, then it accomplishes recovery after a short distance at C. This experiment verifies the result of the simulation.

V. Conclusions and Future Work

This paper proposes a new design of in-pipe robot system-Inspector, which solves some difficulties of in-pipe inspection. Inspector has great flexibility because of the modular design, which allows it to pass through bends and tees. Then, modular design gives Inspector the ability to be customized according to the situation and the goal of inspection. For instance, operators can change different probes to get different types of data or add more locomotion modules to carry more facilities. In addition, Inspector can work in a vertical pipe and recover from occasional capsizing, which enhances its reliability. Besides, a variety of sensors have been mounted to learn about the state of Inspector and handle problems in pipes. On top of that, this paper also comes up with a strategy of automation using four laser range finders as a guidance module. As far as we know, there is no mature product in this field at least in China while a great number of pipes need to be inspected. Therefore, the system also has a great market and commercial value.

Except for the design and functions mentioned above, there are more aspects of Inspector worth further exploring. Our future work will concentrate on the followings.

- Optimize the integration of subsystems, and make them work more effectively.
- Achieve lower power consumption and replace the electric cable with portable batteries.
- Solve the problems of wireless communication between inside and outside of metal pipes.
- Integrate more sensors with Inspector to gain more automation.

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