Development of Articulated Robot for Inspection of Underground Pipelines

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ABSTRACT

Recently many Inpipe inspection robots are introduced and they are expected to realize the improvement of efficiency of inspection. However most of them are lacking in mobility, which makes it difficult to be applied to the actual usage. In this paper, we propose an articulated inpipe inspection robot that has the improved capability of locomotion. The robot has three wheeled legs adopting pantograph mechanism that makes it possible to overcome various obstacles in the pipelines. The active universal joint between the articulated bodies of the robot provides the omni-directional steering capability, and thus it gives the high flexibility of motion in the branches, elbows, valves, and vertical pipelines. We developed two Prototypes and conducted several experiments to evaluate their performances.

1. INTRODUCTION

There are a variety of pipelines that should be inspected and maintained to ensure their safety and integrity. Up to now, a number of researches have been carried out on inpipe inspection systems using robots. Major design issues of the systems are locomotion, power supply, communication, instrumentation etc., and this paper only deals with the aspect of locomotion. Currently, various types of remotely controlled robots begin to be used for servicing inpipe applications. Most of these robots use drive wheels pressed passively against the wall of the pipe by springs and linkages. One approach was scissors-like structure with three wheels, one at the joint and the others at the end of the two limbs[1]. This robot called MOGRER already commercialized aimed at the application in the gas industry[2]. Also, Fujiwara et al.[3], Taguchi, and Kawarazaki[4] addressed similar robots. Kawaguchi et al.[5] developed a mobile robot with magnetic wheels, which had special features in the steering control. As a system adopting a little different type of robots, Ilg et al. addressed an autonomous sewer inspection system. This system used an articulated mobile robot with three DOF active joints at each joint[6].

Depending on applications, specially designed walking mechanisms have been considered[7], but they were too complicated to be applied for the actual usage. Typical obstacles inside the pipelines are elbows, branches, reducer, vertical pipelines and valves. A fundamental requirement of the inpipe inspection robot will be the ability to move through wide range of configurations of pipelines by surmounting the obstacles while simultaneously carrying the given tasks out. Among many robots announced up to date, however, very few of
the robots seem to satisfy the requirements. The design of the robot is determined by the geometrical conditions of pipelines such as diameter, curvature etc. as well as the present state of the technology. The configuration of pipelines restricts the whole size of the robot. The current technology determines the possibility of implementation because actuator, drive electronics, embedded controller, power supply, sensor, and communication tools would have to be placed in an extremely small space. From the present technological point of view, therefore, only a very large robot in size is possible. One solution of this problem is the use of articulated structure such as snake-like or multi-joint robots though the control of the robot gets more difficult.

![Diagram of inpipe inspection system](image)

Figure 1. The schematic diagram of inpipe inspection system

Figure 1 shows the schematic diagram of inpipe inspection system being developed in our laboratory. This system includes several components such as driving robots, tether cable, and worksite module etc. Two articulated driving robots in the front generate traction forces and the robots in the back gives pushing forces when moving forward, and vice versa. The active joint between the tractive robots gives steering capability of the robot. In this paper, we only describe driving robots and its characteristic features. Section 2 addresses the statue of gas pipelines and limitations. Section 3 overviews Prototype I. Section 4 addresses the mechanical structure of Prototype II and shows the experimental procedures for the performance evaluation. Then, we will conclude with summary in section 5.

2. PIPELINES AND ITS LIMITATION

2.1. Pipeline condition

The use of pipelines has increased rapidly since the use of the natural gas as the main resource of energy. Generally, gas pipelines contains high-pressure inflammable gas, and thus, gas leaking may cause huge disaster. In addition, as most of them are laid under the ground, the maintenance and service, after their construction, becomes one of the major problems in
gas industries. Pipelines consist of main pipelines and distributors. The main pipelines supply the gas from the gas base to the major cities. They are simple in shape and easy to service. And so, various dedicated inspection systems have already been developed and commercialized [8]. On the contrary, we have no adequate method of inspection for the distributors that is small in size and have complex configurations. Especially, as the distributor is located in densely populated areas, the inspection is difficult and the gas leaking may cause enormous disaster.

2.2. Geometric limitations

To move through pipelines successfully, a robot should have to overcome the obstacles inside the pipelines. Typical obstacles inside the pipelines are elbows, branches, reducer, vertical pipelines and valves. These constraints should be considered in advance on the design of a robot as they determine the size of the robot.

![Figure 2. Situation inside an elbow](image)

The curvature of pipeline is the most important information on the design because the robot is caught when it is too long and tightening up when it is too thick. The curvature of pipeline is normally kept to be 1.5 times larger than the diameter. Now, let us model each articulated body of the robot as a cylinder shown in Figure 2. Then, the inpipe inspection robot will be the shape of chained cylinders and we can derive relations among the diameter of pipelines, curvature, and the size of cylinder. As depicted in Figure 3, the worst location of the robot is where it is located with the angle 45°. In this situation, we can think about two cases: in case of (a), the width of cylinder w is relatively smaller than the diameter h and both ends of the robot are located on the straight parts of the pipelines. In the case of (b), both ends of the robot are located at the curved part of the pipelines. Depending on the situations, we can derive the constraint equations determine the size of the robot.

2.3. Wall pressing forces

One of the most important issues in the design of the mechanism is how to obtain the traction power enough to pull instrumentation as well as the robot itself. Especially in vertical pipelines, it is desirable to control the wall pressing forces and ensure sufficient tractive forces because excessive forces may consume the power and damage the mechanism, or lack of forces may let the robot fall down. On the condition that the wheel don’t slip over pipe surface, the tractive force by wheel is proportional to the friction coefficient and pressing force between the wheel and the pipe surface. Since the friction coefficient depends on the material of wheel and the surface condition of pipe, we have to design the link mechanism
that is able to adjust the wall pressing force. In addition, the link mechanism of driving part should minimize the variation of tractive force caused by the various pipe diameters. Therefore, link mechanism has to meet the following three requirements. At first, it should be possible to push against the pipe wall powerfully. In the second, the variation of pressing is minimized to provide stable traction force and flexible locomotion. At last, the structure should be simple and small in size to occupy minimum space in the pipe.

3. PROTOTYPE I

Considering the limitations, we have developed two prototypes of the robot and, in this section, we briefly described the first Prototype.

![Diagram](image)

Figure 3. Photo and Kinematic scheme of Prototype I

Figure 3 shows the photo and kinematic structure of the Prototype I, simplified in a two dimensional schematic diagram. The Prototype I has 6 links, and driving wheels are attached to the end of links. Each driving wheel is driven by motor using timing belt and three slider-crank mechanisms are laid apart with 120 degrees. The robot has structure of each couple of spring push links against the pipe with equal force. The robot has simpler driving mechanism than the previous ones and the locomotion performance in elbows and vertical pipelines is distinguished, though steering in branches is impossible.

4. PROTOTYPE II

This section describes the improved version of the Prototype I, which has the capability of steering. Figure 4 shows the schematic diagram and photo of Prototype II. The robot is designed for 8-inch (±20%) gas pipelines. It marks over 3 m/min and overcome the most of obstacles in the pipelines.

4.1 Wheeled Leg Mechanism

As depicted in Figure 5, the proposed mechanism is composed of three wheeled legs and each leg adopts modified pantograph mechanism with sliding base and additional linkages. In
the proposed mechanism the wheels just contract or expand along the radial direction when it is pressed. It is a very advantageous feature because undesirable distortion forces are not exerted on the body when the robot goes over obstacles such as steps, reducers, protrusions etc. On the purpose of controlling the wall pressing forces, we use a linear actuator composed of a motor, a screw, and two position sensors (rotary potentiometer, linear potentiometer). One of the sensors measures the current configuration of the mechanism and the other senses the deflection of the spring. Figure 5 introduces the structure of the leg mechanism.

![Figure 4. Prototype II](image)

![Figure 5. The Structure of the leg mechanism](image)

4.2. Steering mechanism

The steering mechanism, called active universal joint is a 2 DOF joint driven by two motors. As shown in Figure 6, this joint consists of the external gear-bearing-gear system and the internal universal joint to protect each module from torsion. Without the structure of the internal universal joint, these gear heads are free to move with respect to each other upon a bearing which lies on a plane that is tilted $\theta$ degrees from the perpendicular planes of each gear axis of rotation. Ikeda and Takanashi originated this mechanism[9][10] and we improve its performance by modifying the mechanical structure and components. The active steering mechanism connects two articulated bodies of the robot as shown in Figure 4. By actively controlling the joint motion, the navigation direction of the front body is determined. In the
elbow or branches, the operator steers the robot to the desired direction. The kinematics diagram of the joint is as illustrated in Figure 6. The \( J_1 \) axis of each frame points along the axis of rotation: \( J_1 \) for the lower gear head, \( J_2 \) for the bearing, and \( J_3 \) for the upper gear head. \( \theta_1 \) and \( \theta_2 \) are respectively determined by the displacements of each motor. However, the bearing angle \( \theta_2 \) depends on relative angles between \( \theta_1 \) and \( \theta_3 \), and it is not exactly controlled.

![Figure 6. Active steering mechanism](image)

The proposed joint is able to yaw and pitch \( \pm 2\varphi \) degrees, and roll is prohibited by internal universal joint. Thus, it has the advantages that the body does not rotate along the axial direction and the signal lines such as power lines and communication cables are free from twisting.

4.3. Experiments

4.3.1 Outline of system

The proposed ideas have been implemented in the actual system and in this section, we describe the development of the Prototype system and experimental procedures for its performance evaluation.

![Figure 7. Overall system setup and test track](image)
The Developed System, shown in Figure 7, has two bodies and it is connected by active universal joint. Each body has three wheeled legs and the legs are foldable. One motor (Maxon motor) with a screw and potentiometers controls the wall pressing forces, and the other motor (Maxson motor with encoder) generates driving power, which is located in the middle of the body. The power is delivered via worm wheel and timing belt. For each body, we use three motors for drive, steering, and controlling the wall pressing forces, respectively. Figure 7 shows the experimental setup. The operator controls the robot by a joystick, and observes the condition of pipelines by CCD camera attached in front of the robot. The weight of the Prototype is 3.5 Kg and its tractive force are over than 6 Kgf. In addition, it has 44-degree ranges of pitch and yaw.

In the experiments, two tasks have been performed: one is for the steering and the other is for the navigation in the test track.

4.3.2. Steering module test

In the first experiment, the performance of the steering mechanism is evaluated. During initial 5~16 seconds, the joint is commanded to follow the yaw angle given by the joystick and then, during the last 16~18 seconds, the command for the pitch angle is given. Figure 8 shows the successive results of the experiment.

![Figure 8. Active universal joint](image)

4.3.3. Navigation test

![Figure 9. Position control of active universal joint](image)
For the second task, we have constructed a track for testing the navigation performance of the robot. The track has horizontal, branch, elbow, and vertical pipeline. The robot is commanded to go through on the fixed position of the track at the determined time. And, Figure 8 shows the change of steering angle during the navigation. The changes of yaw and pitch angle imply that the robot was adequately steered on each stage.

5. CONCLUSION

In this paper, we proposed two Prototypes of the inpipe inspection robot. The characteristic features of the robots are the steering mechanism with the 2 DOF active joint and flexible wheeled leg mechanism. These mechanisms guarantee the navigation inside the pipelines by overcoming obstacles such as elbows, branches, valves and vertical pipelines. We implemented the proposed mechanisms in the actual robot and its feasibilities were tested. In this stage of development, the robot has only a CCD camera as the basic equipment for inspection. As the future works we will improve the inspection capability of the system with NDT units.

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