Actively Steerable Inpipe Inspection Robots for Underground Urban Gas Pipelines

S. G. Roh, S. M. Ryew, J. H. Yang, H. R. Choi
School of Mechanical Engineering,
Sungkyunkwan University
300, Chonchon-dong, Jangan-gu, Suwon, Kyonggi-do,
Korea, 440-746, hrchoi@mecha.skku.ac.kr

Seoul City Gas R&D Center

Abstract

In this paper we introduce robots called MRINSPECT (Multifunctional Robotic crawler for Inpipe Inspection) III and IV which are under development for the inspection of urban gas pipelines. The proposed robots can freely move along the basic configuration of pipelines such as horizontal or vertical pipelines. Moreover it can travel along reducers, elbows, and steer in the branches by using steering mechanisms. Especially, their three dimensional steering capability provides outstanding mobility in navigation that is a prerequisite characteristic in urban gas pipelines. Their critical points in the design and construction are introduced with preliminary results of experiments.

1 Introduction

There are a wide variety of pipelines such as urban gas, sewage, chemical plant, nuclear power plant etc., which are indispensable in our life. Also, pipelines are the major tools for transportation of oils and gases and a number of countries employ pipelines as the main facilities for transportation. In our country, the urban gas pipelines currently go up to 13,000 Km long but since most of them have been constructed in 1980’s, there happen a lot of troubles caused by aging, corrosion, cracks, and mechanical damages from third parties. Continuous activities for inspection, maintenance and repair should be performed from now on. However, those activities need enormous budgets that may not be easily handled by gas companies as they are mostly small and medium in size. Efficient equipments for inspection and integrated maintenance program are required in gas industries.

Figure 1: MRINSPECT III

Up to now various inpipe robots have been reported [1,2] but those robots just have the capability of traveling along straight pipelines with elbows. Few of them have been designed under the consideration of branched pipelines. In fact branched pipelines are one of the most popular configuration in underground urban gas pipelines and thus to conduct efficient traveling inside those pipelines steering capability is prerequisite. For last several years, we have developed several inpipe inspection robots with steering capability, and this paper introduces the robots named MRINSPECT III and IV among them which have been recently developed( refer to [3] as for MRINSPECT I and II). Both robots have totally different features in steering that may be regarded as the original ones, respectively. In this paper MRINSPECT III is briefly overviewed and a new robot MRINSPECT IV is described in detail. Several specific features are addressed concentrating on the steering and preliminary results of experiments are outlined.

This paper is organized as follows. In the next sec-
tion we briefly introduce MRINSPECT III. Section 3
cover the issues related to the development of MRIN-
SPECT IV and preliminary experiments. Finally we
conclude with summary in section 4.

2 MRINSPECT III

As illustrated Fig. 1 MRINSPECT III consists of
two vehicle segments and a steering mechanism called
Double Active Universal Joint (DAUJ) between the seg-
ments. This robot is configured as an articulated type
where two independent vehicles are connected via a
double active universal joint providing omni-directional
steering capability. DAUJ acts like a stiffness contr-

Figure 2: Inpipe Inspection System

lable two-of joint and it makes it possible to control
the compliance of active joints in steering [4]. Each
articulated body of the robot has three wheeled legs
located circumferentially 120° apart. The legs employ
a pantograph mechanism with a sliding base that en-
sures natural folding and unfolding of the body. With
the proposed mechanism the legs just contract or ex-
pand along the radial direction when they are pressed.
It is a quite advantageous feature because undesirable
forces causing distortion does not exert on the body
when the robot goes over obstacles such as steps, re-
ducers, protrusions inside the pipelines. The driving
motor of the vehicle is included in the rear articulated
body which gives the major driving force to the sys-
tem. The front body does not have any power and it
just guides the motion. The wall pressing forces are
obtained by the reflective forces of the spring that sup-
ports the moving base of the pantograph mechanism.
Thus, the wall pressing forces can be easily preset de-
pending on the payload by adjusting the spring con-
stant and initial deflection. Fig. 2 shows the whole in-
spection system utilizing MRINSPECTION III which
is composed of two MRINSPECT III’s, control mod-
ules, and inspection tools.

3 MRINSPECT IV

3.1 Mechanism Overview

Figure 3: Construction and specification of MRIN-
SPECT IV

MRINSPECT IV shares several aspects with MRIN-
SPECT III but most of the mechanism has been re-
newed to miniaturize the robot as shown in Fig. 3.
The robot is largely composed of 1) a body frame that
mounts a CCD camera assembly and driving modules
with foldable linkages, 2) a camera assembly which
is for the navigation and the visual inspection of the
pipelines, and 3) three modularized driving modules
illustrated in Fig. 4 which are located circumferentialy
with 120° apart.

Figure 4: Driving module

A driving module consists of a DC motor with an
encoder and a reducer, several wheels and casings. As
it can be easily disassembled from the body frame, it
ensures the convenience in maintenance. The driving
units can be controlled independently and thus they
amplify the tractive forces as well as provide steering
capability. To provide the sufficient tracting forces
and flexibility in navigation we designed a body frame
illustrated in Fig. 5. At the end of the legs on the
body frame three driving modules are fixed 120° apart circumferentially.

![Moving direction of Wheel axis](image)

**Figure 5: Link mechanism**

Two wheels of the driving module move independently along the radial direction due to constraints of links and interaction between elastic force at the main spring of the body frame and the reaction forces of the wall. Distance between the main shaft of the robot and the wheel changes according to the link construction, and it makes the wheel have effective contact with the wall inside the pipelines whatever diameters changes. It assures stable traveling as long as providing sufficient traction forces. Front wheel of each driving module have been synchronized each other. As shown in Fig. 3, wheels in front and back of each driving module are named the front wheel set and the back wheel set, respectively. Constraint of the wheels inside each wheel set makes the robot capable of neglecting the effect of gravity, which makes the central axis of the robot always coincide with that of the pipelines.

![Driving Vehicle](image)

**Figure 6: Comparison of MRINSPECT III and IV**

MRINSPECT IV has upgraded MRINSPECT III in many aspects, especially in the steering mechanism. MRINSPECT III performs three-dimensional steering with a double active universal joint, while MRINSPECT IV does with speed differences of each driving module. Fig. 6 illustrates the distinction of the steering action between MRINSPECT III and IV. MRINSPECT III turns the front body by using DAUJ like a manipulator. In this case the robot should not rotate along the driving direction due to the contact constraint between the wheels of the robot and the wall, which is coped with DAUJ. On the contrary MRINSPECT IV steers its own body with the velocity differences among the driving modules. Thus, though it does not require complicated mechanisms, its control becomes quite difficult. The analysis related to the steering control is addressed in the later section.

![Straight to elbow](image)

**Figure 7: Straight to elbow**

### 3.2 Navigation in Elbow

Basically the size of the robot is the critical points in the design in realizing the movement in the elbow. The basic relations and analysis can be found in the reference [3] and in this section we focus on the additional features in the navigation along the elbow.

![Robot in elbow](image)

**Figure 8: Robot in elbow**

To travel smoothly along the elbow it should be considered the curvature of the elbow varies depending upon the inner area of the pipelines having contact with the robot.

When speeds of all of the wheels are same, the wheels in the outer side may be caused to slide, which
3.3 Navigation in Branch

As shown in Fig. 11 branches can be considered to consist of two elbows and V-shaped area between the elbows. The V-shaped area has a flat surface rather than curved one and the flat surface can be found out only in the V-shaped area throughout the pipeline. Consequently, the V-shaped area may be an obstacle to the robot because it has been designed to be suitable for the curved surface. To travel in the branch the robot basically follows the method similar to the method in the elbow but there are several characteristic features that makes it difficult to control its motion. These can be summarized as follows. First, as the robot moves along the branch, it meets a variety of cross sections depending on the posture of the wheel as shown in Fig. 12. In the second, the robot has been designed to move while making six wheels have contact with the inner side of the pipe radially. Nevertheless when the robot enters a branch, some of the wheels may not have contact with the wall. According to Fig. 12 the cross section does not have a circular shape any more in the branch and some of the wheels may carry idle rotations. In this case the robot loses its degree of motion and consequently we may not able to...
control its travel route exactly. When the robot turns in a branch, its center is assumed to move along the curve like $Arc ~ R_T$ as illustrated in Fig. 12 that has different meaning from $Arc ~ R, Arc ~ A$ and $Arc ~ B$ of the elbow because these Arcs of the elbow are a deterministic path produced by the robot while its wheels keep contact with the inner walls. When the robot enter the branch, initially the diameter of the pipeline does not change a lot until the front wheel set reaches section B-B after passing through section A-A illustrated in Fig. 13, but the robot cannot rotate in this region whatever speed differences are given.

![Figure 13: Constraint space in branch](image)

When the front wheel set comes to the section C-C, the diameter of the pipeline changes greatly to let the robot travel toward _turn drive space_ represented in Fig. 13. Even at this region, the robot can not rotate by itself with speed differences. In this region, the robot travels toward the _turn drive space_ because the front wheel set is still placed close to inner side of the pipeline. Also, the front wheel set of the robot has still contact with the inner side of the pipeline and as the wheel set is confined absolutely up to this section, it cannot rotate by using speed differences. In fact, despite speed difference of the robot wheel only slip is produced between the wheels and inner sides of the pipelines, and the robot cannot rotate to the direction that it has to move. As a result, in this region the robot can still select either straight travel or rotation and thus this space is said to be _drive choice space_.

When the front wheel set is close to section D-D, either one or two wheels, which are placed at the _turn drive space_, do not contact inner side of the pipe. Such a phenomenon indicates that there exists no inner side of the pipe contacting the wheel, which may prevent the robot from moving to the _turn drive space_. In this region, the robot can turn along the desired direction with speed differences. Thus as soon as the robot enters the branch, it decides the direction of rotation using CCD camera attached in the front of the robot, and then adjusts the rotational speed of each three driving modules. In Fig. 14 $P_a$, $P_b$ and $P_c$ indicate the points where each wheel contacts the inner side of the pipeline (this is based on the assumption that each wheel contacts the points).

![Figure 14: Three dimensional representation of related velocity vectors](image)

It also shows the rotational direction of the robot when only the wheel at $P_a$ rotates while two wheels remain without rotating. When speeds at $P_a$ is $V_A$ and speeds at $P_b$, $P_c$ are 0 respectively, the robot turns with $\omega_A$ of angular speed along the direction of the vector connecting $P_a$ and $P_b$. As explained, the robot actually starts to rotate at section D-D, and the speed differences does not have a lot of influence on the rotation in front of the section D-D. Thus, we just need to start modulating the speeds of the wheels at the section D-D and to turn the robot to the desired direction, the rotation speed should be controlled accordingly as shown in Fig. 15. To turn the robot, first $V_A$ at $P_a$ assuming that it is the place closest to the rotational direction $-z$, is set to be 0. Using the CCD camera we already know the angles $\theta$, $\theta + 120^\circ$, and $\theta + 240^\circ$ between $z$-axis and wheels, respectively. $\omega_P$ of the angular speed can be freely selected to let the robot rotate, but $V_A$, and $V_B$ have to be decided to select the robot’s travel speed at contact points between each wheel and inner wall of the pipeline. The
following equation can be used to derive $V_A$ and $V_B$.

\begin{align}
\omega_a &= V_A \times \frac{3}{2} P_a \quad (1) \\
\omega_b &= V_A \times \frac{3}{2} P_b \quad (2) \\
P_b \cdot \omega_b &= 0 \quad (3) \\
P_b \cdot \omega_a &= |P_b| |\omega_a| \cos 150^\circ \quad (4)
\end{align}

Those are the basic equations for navigation in the branch and in reality a lot of unexpected patterns of movements can be met. It need further research to completely analyze the motion in the branch.

4 Preliminary Experiments

In the experiments we demonstrated the movement in the elbow with $90^\circ$ and the steering in the branch. Fig. 16 shows the scene of the robot running along the elbow and Figs. 17 and 18 depicts the steering in the branch which has $90^\circ$ of the curvature angle.

![Figure 16: Robot in elbow](image)

![Figure 17: Straight drive in branch](image)

5 Conclusion

In this paper we introduces two inpipe inspection robots, MRINSPECT III and IV. The system with MRINSPECT III has already been developed as shown in Fig. 2 but the system for MRINSPECT IV is under development. Both robots has the characteristic features in steering which are not discussed in the other robots. The steering is very important in underground pipelines, especially in urban gas pipelines and the proposed robots proves their effectiveness through real implementations. As the further work, we are going to implement NDT inspection tools on our robot and related works will be continued.

Acknowledgments

The authors are grateful for the support provided by a grant from Seoul City gas R&D center and the Safety and Structural Integrity Research Center at the Sung Kyun Kwan University.

References


