In-pipe Robot with Capability of Self Stabilization and Accurate Pipe Surface Cleaning

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Abstract—After 50 years the connections between fresh water pipes (800-1000mm diameter) need to be repaired due to aging and dissolution of the filling material. Only in Vienna 3000km of pipes need to be improved, which requires a robotic solution. The main challenge is to accurately place the robot in the center of the pipe while overcoming the push back forces and vibrations caused in the cleaning process, so that the cleaning tool is able to focus on desired area of the pipe surface. This paper presents the overall design of an in-pipe cleaning robot DeWaLoP, which includes a suspension system to position itself as a rigid structure stably in the center of the pipe, while the H configuration of the robot arm is able to stabilize the cleaning tool in the cleaning process, to reduce the vibration and push back forces.

I. INTRODUCTION

Fresh water pipelines are prone to damages due to aging, excessive traffic and geological changes. Resulting from these damages, the pipe-joints may not be completely hermetic and water loss along the pipeline may occur. Leakage is not only a problem in terms of wasting an important resource, it also results in an economic loss in form of damages to the supplying system and to foundations of roads and buildings too [1] [2].

The installation or replacement of pipelines implicates high cost and use of heavy machinery, such as cranes. In addition, side effects may occur, such as constructions sites placed along streets, blocking pedestrian and traffic tracks [3]. The size of pipes transporting water between residential areas and industrial parks is normally ranged from 800mm to 1200mm in diameter, which make it possible for one man to enter. Consequently, human operators can access the pipe and attempt to clean and repair it, as shown in figure 2. Nevertheless, this creates a special situation that presents safety and health risk to the human operator [4]. Currently, the applications of robots for the maintenance of the pipeline utilities are considered as one of the most attractive solutions available. Nevertheless, to substitute skilled human operators, pipe redevelopment requires mechanisms with high degree of mobility, able to move along the pipeline, overcoming obstacles, extreme environments, and with high accuracy clean and repair specific areas of the pipe [5] [6] [7].

The most common method to clean the pipe is using water jet, as this method does not require accurate positioning of the robot inside the pipe. However, the water pressure has disadvantage of damaging the pipe-joint hemp pack which is caulked up with a lead ring. Thus, we adopt a cleaning method which is using wire brushes disks and grinding heads to remove the corrosion of the pipe by friction. By auto suspension system, our robot is able to fix its in-pipe position accurately to support the cleaning tool system to focus on specific areas.

This paper presents overall design of our in-pipe robotic system, as shown in figure 1, with a focus on its configuration and mechanical design of the cleaning mechanism.

II. RELATED WORK

In-pipe cleaning robots can be categorized to two types: 1) Pressure-based cleaning robots and 2) Tool-based cleaning robots. In this section, we present the typical in-pipe cleaning robots developed both from academia and industry.

A. Pressure-based cleaning methods

J. Saenz [8] presents a cleaning system able to work efficiently and control the pressure of the nozzle through a relative accurate positioning to the pipe wall. They commented "A common risk when cleaning with high pressure water is the possible damage to the surface from overly applied pressure. This risk can be minimized with such a cleaning system where the cleaning parameters can be carefully controlled and monitored". Even if the pressure can be controlled, for cleaning pipe-joint this is not recommended, due to the pressure exerted by the water, pushing the hermetic seal of the pipe-joint.

B. Tool-based cleaning - Impact abrasion methods

1) GRISLEE - Gasmain Repair and Inspection System for Live Entry Environments: The GRISLEE is designed to be modular, so different kinds of in situ repairs are possible. The cleaning system consists of flails, which expand when
rotates and cleans the surface by impact abrasion method. The system has a compact size, and is able to work in different pipe sizes [9].

2) Umbrella mechanism: The umbrella mechanism consists of a structure able to increase its height in order to adapt to different pipe diameters. The cleaning system is similar to an umbrella kind open-and-close mechanism, which makes the robot highly adaptable to different pipe sizes [10].

Commercial cleaning system such as Robocutter [11], KASRO robot [12], OptiCut [13] and IMS Turbo cutter [14] are smaller robots but use similar design like the umbrella mechanism. Lacking of stability, due to the push back effects and vibration caused in the cleaning process.

C. Tool-based cleaning - Cutting methods

1) Cutter cleaner arm: N. T. Thinh [15] describes an in-pipe robot for cleaning and inspecting, in which the cleaning mechanism is an arm consisting of small cutting plates. The arm is located on the front of the robot, perpendicular to the pipe’s horizontal with the same length as the inner-pipe’s diameter. From this configuration, the cleaning method consists of rotating the arm, milling all corrosion while the robot moves inside the pipe. Although the mechanism is able to remove strongly incrusted corrosion. The drawback of this configuration is the low flexibility of the cleaning tool to pipe displacement. In other words, the cleaning mechanism will damage the pipe if the pipes are not perfectly aligned.

C. D. Jung [16] proposes an in-pipe cleaning robot with the 6-link sliding mechanism which can be adjusted to fit into the inner face of the pipe using pneumatic pressure. The proposed in-pipe cleaning robot have self forward/backward movement as well as rotation movement of brush. However, the disk cleans all over the in-pipe wall without being able to focus on a specific area.

In contrast to the state-of-the-art cleaning mechanisms, DeWaLoP in-pipe robot is able to fix itself stably in a specific location using self suspension system. Independently from the main body of the robot, the cleaning tool is flexibly configured which can be adjusted in a cylindrical 3D space, able to move up to 100mm in the pipe’s horizontal axis, and reach to the surface of the pipe with diameter in the range of 800mm to 1000mm.

Besides its high positioning capability and flexibility, the cleaning mechanism is able to overcome vibrations and jump back forces from the cleaning tool with its integrated suspension system, mimicking the reaction of a human operator when such events happens.

III. DeWaLoP IN-PIPE ROBOT SYSTEM

The DeWaLoP robot is intended to be a low cost robot with high reliability and easiness in use. The robot system includes a conventional in-pipe inspection system, which is carried out by using a cable-tethered robot with an onboard video system. An operator remotely controls the movement of the robot.

The robot consists of five main subsystems: control station, mobile robot, maintenance system, vision system and cleaning tool system, as shown in figure 3:

A. Control station.

The control station monitors and controls all the components of the in-pipe robot. The controller includes a slate computer for monitoring and displaying the video images from the robot’s Ethernet cameras. Additionally, several 8 bits micro-controllers with Ethernet capabilities are included, sending and receiving commands to the in-pipe robot from the remote’s joysticks and buttons [17].

B. Mobile robot.

The mobile platform is able to move along the pipe, carrying on board the electronic and mechanical components of the robot, such as motor drivers, power supplies, and etc. It uses a differential wheel drive which enable the robot to promptly adjust its position to remain in the middle of the pipe while moving.
C. Maintenance unit.

The maintenance unit consists of a wheeled-leg structure able to extend or compress with a Dynamical Independent Suspension System (DISS). When extending its wheeled-legs, it creates a rigid structure inside the pipe, so the robot tools work without any vibration or involuntary movement from its inertia. When compressing its wheeled-legs, the wheels become active and the maintenance unit is able to move along the pipe by the mobile robot.

The maintenance unit structure consists of six wheeled-legs, distributed in pairs of three, on each side, separated by an angle of 120°, supporting the structure along the centre of the pipe, as shown in figure 3. The maintenance unit combines a wheel-drive-system with a wall-press-system, enabling the robot to operate in pipe diameters varying from 800 mm to 1000 mm. Moreover, the maintenance unit together with the mobile robot form a monolithic multi-module robot, which can be easily mounted/dismounted without the need of screws.

D. Vision system.

The in-pipe robot includes four cameras, in order to navigate in the pipe, detect defects and redevelop specific areas. For the navigation stage, two cameras are required, one located at the front, to inspect the way in the pipe, whereas the second located at the back, to inspect the way out. For the detection stage, an omni-directional camera is located at the front-end of the robot enabling the pipe-joint detection [18]. Finally, for the redevelopment stage, another camera is mounted on the cleaning mechanism. This camera acts as the human operator eyes, enabling the operator to follow the details of the redevelopment process.

E. Cleaning tool system.

We will present this part in the following section.

IV. DeWaLoP CLEANING MECHANISM

The concept of the DeWaLoP cleaning mechanism is based on the cylindrical robot principle, able to rotate along its main axes forming a cylindrical shape. The robot arm is attached to the slide so that it can be moved radially with respect to the column.

However, the DeWaLoP mechanism modifies the standard cylindrical robot into a double cylindrical robot, where both arms are connected to the central axis and opposite each other. In this configuration, an extra actuator is added to the standard model to extend/compress this second arm. Contrary to the standard cylindrical robot, the location of the rotating actuator is not in the central axis of the robot, it is located on the arm which is opposite to the arm with the tool, as shown in figure 4a. Hence, this rotating actuator (drive wheel) rotates and with it the entire cleaning mechanism.

If we relate the forward transformation of the cylindrical robot to the DeWaLoP mechanism, the angular motion is modified. The forward transformation for a cylindrical robot is quite simple, because it is equivalent to the transformation from a cylindrical to a Cartesian frame [19].

Likewise, the rotation ratio of the DeWaLoP mechanism is given by the pipe radius $r_{pipe}$ divided to the radius of the drive wheel $r_{wheel}$, similar to a planetary gear, where the outer gear (the drive wheel) revolve from the central (the pipe). Thus, the revolutions needed from the drive wheel ($dw_r$) to complete a full rotation is $dw_r = \frac{r_{pipe}}{r_{wheel}}$.

In this way, we can use $dw_r$ (drive wheel revolutions) to represent the cylindrical robot angular value.
\[ \varphi(t) = \left( \frac{d_w}{r_{\text{pipe}}/r_{\text{wheel}}} \right) \times 360^\circ \] (1)

And the forward transformation for the model is:

\[ x_0'(t) = x_0(t) = x(t) \] (2)
\[ y_0(t) = [(A/2) + r(t)]\cos(\varphi(t)) \] (3)
\[ y_0'(t) = [(A/2) + r'(t)]\cos(\varphi(t) + 180^\circ) \] (4)
\[ z_0(t) = [(A/2) + r(t)]\sin(\varphi(t)) \] (5)
\[ z_0'(t) = [(A/2) + r'(t)]\sin(\varphi(t) + 180^\circ) \] (6)

where \((x_0, y_0, z_0)\) are the coordinates for the cleaning tool arm and \((x_0', y_0', z_0')\) are the coordinates for the drive wheel arm. \(\varphi(t)\) is the joint revolute, \(r(t)\) is the length of the arm with the cleaning tool, \(r'(t)\) is the length of the arm with the drive wheel, \(x(t)\) is the axial distance in the \(x\)-axis (pipe’s horizontal) and \(A\) represents the width of the linear and circular bearings of the mechanism installed on the central axis of the robot.

In this simplified robot configuration, the cleaning tool is located opposite to the drive wheel and perpendicular to the robot’s central axis, as shown in figure 4a. Therefore, the spacing to attach power tools is considerable small. The maximum cleaning tool height is given by:

\[ CT_h_{\text{max}} = Pr - \frac{A}{2} - D r p r \] (7)

where \(Pr\) is the pipe radius and \(D r p r\) is the clearance distance of the mechanism to the pipe wall. In other words, the mechanism in this configuration restricts the height size of the attached cleaning tool to \(CT_h_{\text{max}} \leq 300\text{mm}\). That means, only angle grinders with \(\text{disks} \leq 115\text{mm}\) may be attached [20].

In order to attach bigger power tools to the cleaning mechanism, with heights in the range up to 500\text{mm}, a new configuration is presented.

**Double cylindrical robot H-Configuration.** In this configuration the arms are not mounted directly over the bearing arrangement in the main axis. Instead, they are translated to its sides, around it and parallel to each other, as shown in figure 4b. In this way, the maximum height of the cleaning tool is determined by the "H" geometric configuration, as shown in figure 4d.

\[ CT_{h_{\text{maxH}}} = \sin(\alpha)D - Dr pr \] (8)

where \(\alpha = \tan^{-1}(H/W)\) is the angle between the direction vector \(f1\) which is from the pipe center to the cleaning tool mounted at the end of the arm, to the direction \(f2\) which is perpendicular to the arm, \(H\) is the height of the tool system in compress mode \((H = 500\text{mm})\), \(W\) is the width of the tool system \((W = 300\text{mm})\) and \(D\) is the diameter of the pipe \((D = 800\text{mm})\).

Consequently, it is possible to attach cleaning power tools with height up to \(CT_{h_{\text{maxH}}} \leq 685.99\text{mm} - Dr pr\), such as straight grinders and angle grinders with 125\text{mm} disks or bigger.

From the simplified H-configuration model, where \(l\) is the shifted distance of the arms from the central axis of the robot, as shown in figure 4b. The position of the end effector from the robot cleaning tool is \(p = (p_x, p_y, p_z)^T\) and the position of the drive wheel is \(p' = (p'_x, p'_y, p'_z)^T\), where \(p_x = p'_x\) represents the translation in the pipe’s horizontal axis.

The robot’s cleaning tool direct kinematics is

\[ p = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix} = \begin{pmatrix} 1/2 \sin \varphi + r \cos \varphi \\ 1/2 \cos \varphi - r \sin \varphi \end{pmatrix} \] (9)
and the robot’s drive wheel direct kinematics is

\[
p' = \begin{pmatrix} p'_x \\
 p'_y \\
 p'_z 
\end{pmatrix} = \begin{pmatrix} 1 \\
 1/2 \sin(\phi + 180') + r' \cos(\phi + 180') \\
 1/2 \cos(\phi + 180') - r' \sin(\phi + 180') 
\end{pmatrix}
\]

(10)

**Stability analysis of the H-configuration mechanism.**

The vibrations and jump back forces from the cleaning tool while removing corrosion may appear in various directions. The forces in the pipe’s horizontal (x-axis) are damped by the cleaning tool structure. These are the most noxious forces affecting the robot, because no suspension system is damping it. However, these forces are unlikely to occur when using angle grinders, as shown in figure 2. Due to the rotation of the cleaning tool, which is similar to the mechanism of the drive wheel, affecting only the y-axis, reducing x-axis forces. Nevertheless, these types of noxious forces appear when using straight grinders, in this case, the cleaning head is rotating over the pipe’s surface resulting in vibration forces in all direction.

The vibrations and forces perpendicular to the cleaning tool, in the y-axis, are damped by the drive wheel located on the opposite end of the mechanism, as shown in figure 5. In this case, the damping degree is given by the friction coefficient \( \mu \) of the drive wheel to the pipe’s surface and the force applied by the wheel to the surface. This may vary if the surface is wet or dry, with friction coefficient in the ranges from \( \mu = 0.35 \) to \( \mu = 0.5 \). And the damping forces are in the range of \( 140N \) to \( 200N \) respectively, with a \( 400N \) spring on the drive wheel. In other words, if vibrations or jump back forces in the y-axis stronger than \( 200N \) are affecting the cleaning tool, then the drive wheel may slip a bit, mimicking the arms of a human operator damping these forces.

The vibrations and jump back forces opposite to the cleaning tool, in the z-axis, are damped by its \( 400N \) suspension system. Mimicking again, a human operator retracting the arms when opposite forces from the application axis appear.

V. EXPERIMENT ANALYSIS

We use a cast-iron pipe segment provided by Vienna Waterworks Company to perform the experiment. The pipe segment has length of \( 6000mm \) and diameter of \( 900mm \).

A. Procedure of the experiment

The process of conducting the experiment is described as following (some photos taken from this process are shown in Fig 6):

**Step 1:** The mobile robot and the maintenance unit were arranged as a monolithic robot. The selected cleaning tool was mounted on the cleaning mechanism.

**Step 2:** The robot was moved inside the pipe and stopped over a determined point. The robot adapted its maintenance unit configuration, from compressed to extended mode, so that the wheeled-legs formed the robot to be a centered and rigid structure inside the pipe.

**Step 3:** Once the extending is finished, the cleaning mechanism is enabled and selected. The arm with the drive wheel is extended first until it makes proper contact to the pipe surface, by compressing its spring (\( 400N \)). Then the arm with the cleaning tool is moved to the desired position in cylindrical 3D space.

Detailed information of the DeWaLoP cleaning mechanism and cleaning process, such as simulation and videos, can be found in [21].

B. Experimental results and evaluation

The job of cleaning the inner surface of a pipe with diameter of \( 1000mm \) and length of \( 30mm \), which is an area of size \( a = \pi \times D \times w = 0.094m^2 \), will cost a human operator between 30 to 60 minutes, according to the estimation of Vienna waterworks. In our experiment, the DeWaLop robot completed the job within 5 to 15 minutes, and the corrosion is fully removed. The actual speed highly depends on the displacement of the pipe. For a pipe without displacement, the cleaning tool revolves without adjusting its position according to the pipe horizontal direction, so that it is able to achieve the fastest cleaning speed of 5-7 minutes. While for pipes with displacements, the cleaning mechanism is required to adjust its position and the cleaning process takes up to 15mins.

Hence, the cleaning speed of DeWaLop robot is 6 to 10 times faster than human operators. Besides, the cleaning pattern of DeWaLoP is mostly a straight line, in contrast to the zig-zag pattern left by human operators.

Considering the power consumption and size of the robot, Table I shows the detail parameters of DeWaLoP robot and other existing in-pipe robots. Although, DeWaLoP targets to larger pipes, it still remains in acceptable levels of power consumption, scaling and size.
VI. CONCLUSION

A new in-pipe cleaning mechanism was presented and compared to the state-of-the-art cleaning systems. The presented mechanism improves the state-of-the-art in multiple aspects, such as enabling the cleaning tool to precisely step on the pipe surface by using the double cylindrical H-configuration mechanism in the robot arm, and protecting the pipe from noxious forces caused by the cleaning tool from its integrated suspension and drive wheel configuration.

The presented mechanism, modifies the cylindrical robot configuration into a double cylindrical robot. In which the angular actuator is located on one of the arms and not in the central axis as the classical model. Enabling the mechanism to rotate with high precision similar to a planetary gear. While rotating the system removes the corrosion of the pipe with a cleaning tool mounted on the opposite arm to the drive wheel.

Cleaning results from the DeWaLoP mechanism are presented and compared to human performances, revealing a faster and accurate trajectory of the cleaning path.

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REFERENCES


