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Automatic In-pipe Robot Centering from 3D to 2D Controller Simplification

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Abstract— **After 50 years the connections between fresh water pipes (800-1200mm 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 align the robot axis with the pipe axis to enable the rotary motion of the maintenance tool. The tool system for cleaning and sealing is mounted on the maintenance unit of the robot consisting of six wheeled-legs. These legs extend to the irregular cast-iron pipe and set the robot structure eccentric to the pipe′s center. In order to center the maintenance unit, distance sensors on the legs allow to adapt to the noncircular shape of the pipe. Correcting the leg extension allows to obtain better positioning of the cleaning tool.**

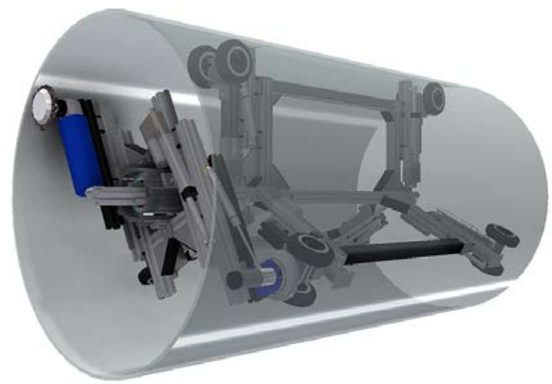

Fig. 1. DeWaLoP -Developing Water Loss Prevention in-pipe robot. The robot is set as a rigid structure inside pipe by extending its wheeled-legs so the tool mechanism on its front (cleaning and sealing) work by rotating from the robot central axis. However, each leg extend differently due to corrosion structures over the pipe wall and to center the robot inside the pipe a 3D controller is required, to take into account all 6 wheeled-legs feedback potentiometer.

I. INTRODUCTION

Fresh water pipelines are prone to damage 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 800*mm* to 1200*mm* 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. Hence, 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].

Before cleaning or sealing the pipe, as prerequisite, the robot must be set perfectly to the pipe center. Otherwise, the movement of the tool mechanism (cleaning and sealing) may required to be adjusted all the time, making the system more susceptible to damage the pipe while cleaning as well as slowing the redevelopment process.

However, placing the in-pipe robot precisely to the pipe center is considered a difficult task. Pipes in reality suffer from corrosion and other damages, which bring them into non-circular shapes. Their distorted circular shape can not be pre-measured, therefore robots need to adjust their position according to the eccentricity of the pipes while cleaning and sealing.

This paper presents an overview design of the DeWaLoP robot and its multi functionality, with special focusing on its ability to automatically self-sitting in the center of the pipe, which has distorted its circular surface. In the experimental evaluation section, a prototype robot will be tested and statistic results will be given.

II. RELATED WORK

DeWaLoP robot must be fixed inside the pipe, in order to overcome jump backs and vibrations from the power cleaning tools (around 1500 Watts). Thus, to handle these amount of forces the structure must be rigid and stable. Therefore, DeWaLoP robot is able to perform multiple tasks, such as inspecting the pipe with its video system, while cleaning the pipe and sealing the pipe with an injection system, thanks to the automatic self centralizing solution.

Most of them do not require to set the robot as a rigid

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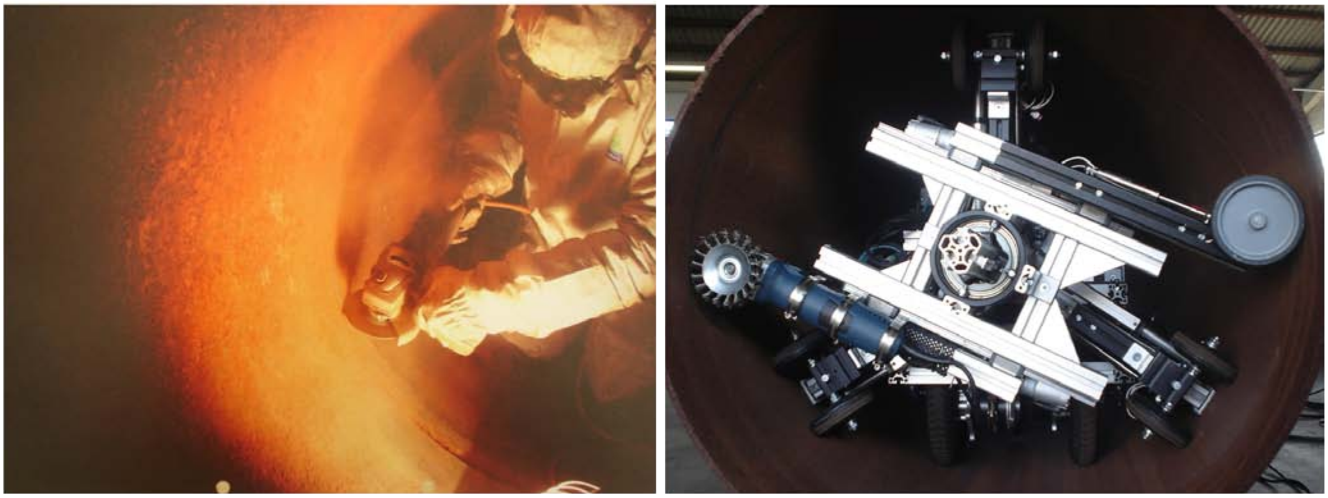

Fig. 2. Human operator inside a 900*mm* diameter pipe, cleaning the pipe wall with an angle grinder - cutting disk (left). DeWaLoP robot inside the pipe, creating a rigid structure from its six wheeled-legs, robot in cleaning mode with an angle grinder - wire brushes disk (right).

structure in an accurate position inside of the pipe. Therefore, without accurate positioning and lack of stability from vibrations, they are only able to clean the pipes superficially and not in detail.

Here, we present several state-of-the-art in-pipe cleaning mechanisms and compare them to the proposed DeWaLoP mechanism.

A. Gasmain Repair and Inspection System for Live Entry Environments (GRISLEE)

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 [8].

B. Robotic systems based on umbrella mechanism

The umbrella mechanism consists of a structure which is 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 [9].

Commercial cleaning systems follows similar mechanical principles,

which is having a mobile robot not fixed to the center of the pipe. While the robot is performing cutting or sealing tasks, the stability of the mobile robot relay on the weight of the robot itself and the friction of the wheels to the pipe, to overcome vibrations and jump backs from the cleaning or sealing tools [10] [11] [12] [13].

C. Robots based on water pressure cleaning method

For water pressure cleaning methods the robot do not require to be fixed inside the pipe. J. Saenz [14] presented a water pressure cleaning system able to work efficiently and control the pressure of the nozzle through a relative accurate positioning to the pipe wall. However, as 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, this method is not recommended for clean pipe-joint due to the pressure exerted by the water may push the hermetic seal of the pipe-joint.

Since the required cleaning must take into account not to damage the pipe-joint hemp pack, caulked up with a lead ring in the 1920's. Thus, the only available cleaning methods are by friction with wire brushes disks and grinding heads to remove the corrosion from the joint socket.

In contrast to the state-of-the-art cleaning and sealing mechanism,

DeWaLoP in-pipe robot is able to fix itself in specific location and adjust the cleaning or sealing tool in a cylindrical 3*D* space independently from the rest of the robot, enabling the movement up to 100*mm* in the pipe's horizontal axis, while reaching the inner pipe surface of pipes with diameters ranging from 800*mm* to 1000*mm*, overcoming the displacements.

III. DeWaLoP Robot

The DeWaLoP robot is intended to be a low cost robot with high reliability and easiness in use. The robot is equipped with an onboard video system for inspection purpose.

The DeWaLoP robot consists of three main subsystems: control station, mobile robot and maintenance system:

A. Control station.

The control station monitors and controls all the systems 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 microcontrollers with Ethernet capabilities are included, sending and receiving commands to the in-pipe robot from the remote control joysticks, switches and buttons [15].

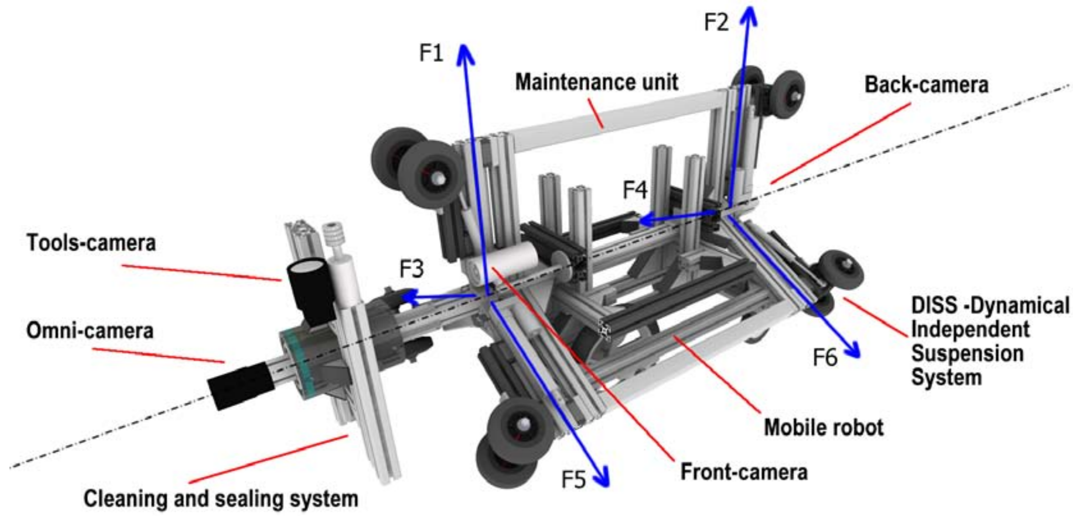

Fig. 3. DeWaLoP in-pipe robot perspective view. Blue arrows mark the force vectors from the linear actuators, used to set the robot as a centered rigid structure inside the pipe.

B. Mobile robot.

Mobile platform able to move along the pipe, carrying on board the electronic and mechanical components of the system, such as motor drivers and power supplies. It uses a differential wheel drive which makes the robot able to adjust its position 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) [16]. When extending its wheeled-legs, it creates a rigid structure inside the pipe, so the robot tools work without much 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 system combines a wheel-drive-system with a wall-press-system, enabling the system to operate in pipe diameters varying from 800*mm* to 1000*mm*. Moreover, the maintenance unit and the mobile robot form a monolithic multi-module robot, which can be easily mounted/dismounted without the need of screws.

D. Maintenance unit - 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. 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. Maintenance unit - Tool mechanism (cleaning / sealing)

The concept of the cleaning and sealing mechanism is based on the cylindrical robot principle, to cover 3*D* cylindrical space. 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. The tool is mounted on one of the arms, while on the opposite arm a drive wheel rotates the entire tool mechanism, similar to a planetary gearbox [17].

IV. Eccentricity problem of the pipe

The corrosion structures on the inner pipe surface influence stochastically the distance of how far the wheeled-legs can extend. It will cause the maintenance unit to be eccentric. In order to avoid eccentric problem, our target is to design a controller to center the maintenance unit in the pipe, robust to corrosion structures with thickness up to 40*mm* (upper limit value of corrosion thickness estimated in reality) . We use the term "eccentricity" to describe the shift distance of the center of the pipe (ground truth) to the center point of the maintenance system.

If a pipe is free of imperfections, then the centering process is equal to extend all the legs with the same distance. However, the problem occurs when one or more wheeled-legs are extended over corrosion. The maintenance unit consists of two (front and rear) sets of 3 wheeled-legs, as shown in Fig. 4*a*. To center the entire maintenance unit is a 3D controlling process. Nevertheless, as each set can be

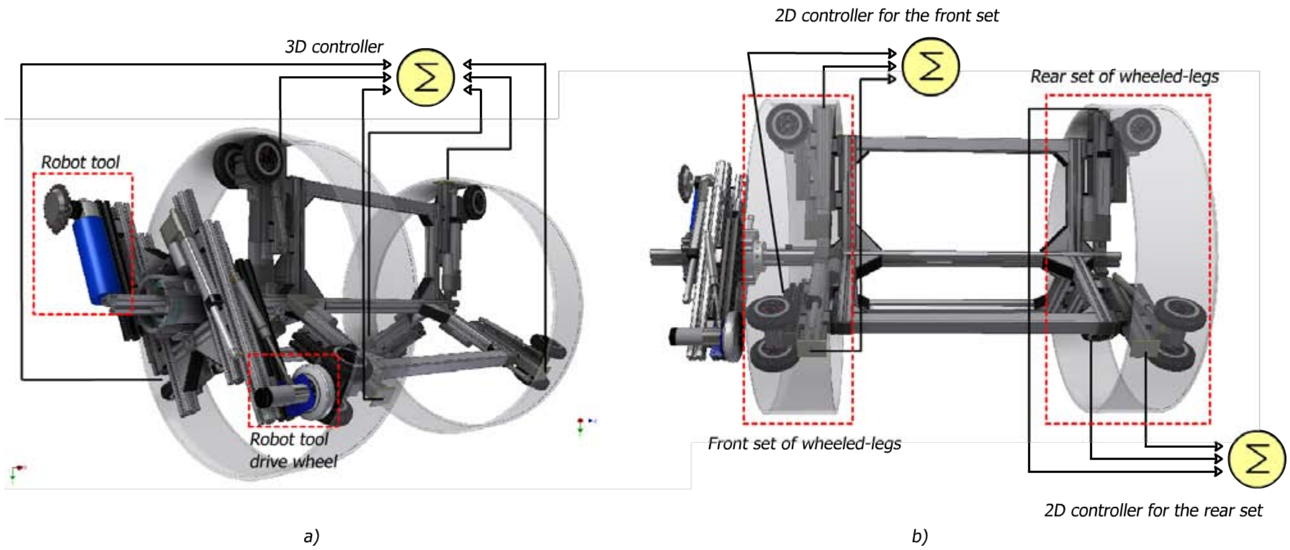

Fig. 4. a) 3D controller for centering the maintenance unit, taking into account all 6 linear actuators - feedback. b) Simplified 2D controller for centering the front wheeled-legs and rear wheeled-legs independently.

treated independently, we can simplify the task to a couple of 2D independent controlling process, as shown 4*b*.

We quantify the eccentricity by measuring the shifted distance from the center of the pipe to the center of the maintenance unit once all legs are extended to the surface of the pipe. The simplest scenario is when only one wheeled-leg steps on an imperfection with the maximum size of 40*mm* and the result is a shifted distance of about 48mm, as shown in figure 6*a*. When two legs are stepping on 40*mm* thick imperfections, the maximum shifted distance of the maintenance unit is about 98*mm*, as shown in figure 6*b*. Consequently, two imperfections of 40*mm* will produce the maximum eccentricity. Since a third imperfection will not increase the eccentricity. Instead, it will contribute to center the maintenance unit.

From figure 5 it can be shown that the eccentricity varies approximately linearly with respect to the imperfection size (e.g. corrosion thickness) and slightly decreases when the pipe diameter increases. In other words, the eccentricity is a function of the pipe diameter, number and size of imperfections.

In order to analyze how the eccentricities affect the robot position, a wire model of the maintenance unit in lateral view is shown in figure 7, where e_r and e_f denote the eccentricities of the rear and front set of wheeled-legs respectively. From the wire model analysis, it is possible to observe that the eccentricity e_f has greater impact in the position of the robot than e_r, due to our specific geometric design of the cleaning tool. And in our geometric specification, the eccentric placement of the maintenance unit brings relatively larger distance shift of cleaning tool on *y*-axis (the direction of perpendicular to the pipe) than in the *x*-axis (horizontal direction).

To quantify the influence of eccentricities e_r and e_f on d_y and d_x, we quantify the shifted distance when e_f is fixed

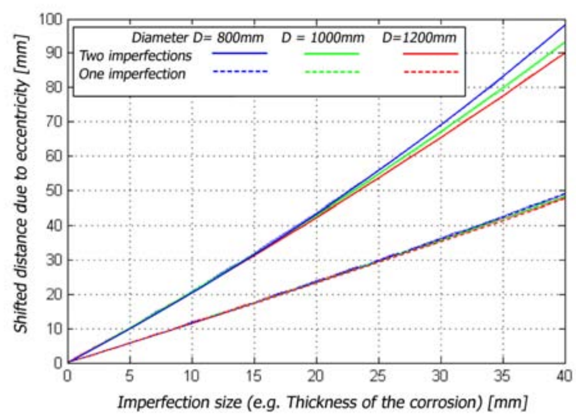

Fig. 5. Shift distance of maintenance unit from center of the pipe due to one and two imperfections.

while e_r is varied from 0 to 100*mm*. The same process is repeated for e_r fixed and e_f varies. The results are shown in figure 8, where the maximum shifted distance d_x in the pipe's horizontal *x*-axis is $d_x = 6mm$ (when $e_f = 100mm$ and $e_r = 0$), and $d_x = 1mm$ (when $e_r = 100mm$ and $e_f = 0$). The impact of shifted distance in d_y is larger, reaching $d_y = 120mm$ (when $e_f = 100mm$ and $e_r = 0$), and $d_y = 20mm$ (when $e_r = 100mm$ and $e_f = 0$).

The eccentricity tolerances are defined as the admissible values for the tool system to rotate without the need of adjustment. For the shifted distance d_x in the horizontal direction, the tolerance is given by the width of the cleaning tool and hose diameter of the sealing tools. The brushes disk has width of 15*mm* and the hose diameter is 14*mm*. The working tolerance for the shifted distance in the *x*-axis is $d_x \leq 7mm$, which is half of the width of the brushes disk and the radius of the sealing hose.

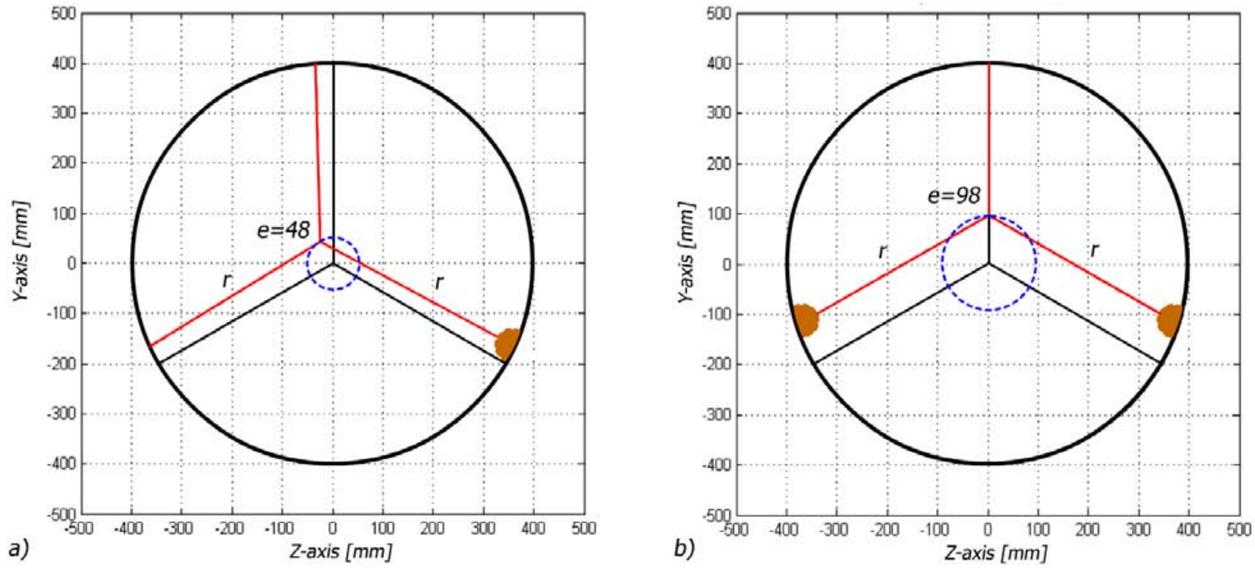

Fig. 6. Wheeled-legs extending inside a 800*mm* diameter pipe. a) Eccentricity e due to one leg extending from a 40*mm* imperfection. b) Eccentricity e due to two legs extending from 40*mm* imperfections (the extended length of the bottom legs are not considering the pipe's surface deformation and the length is equal to the radius of the pipe).

On the other hand, the working tolerance for the shifted distance d_y, in the y-axis, depends on the suspension system of the robot tool. This suspension system integrates a damper able to compress 20*mm*, overcoming cases when $d_y \leq 20mm$. However, the tool system must be readjusted when $d_y > 20mm$. From above analysis and the data presented in Fig 8, we can conclude that the critical eccentricity problem exists in the front set of wheeled-legs from the maintenance unit (denote as e_f). When $e_f > 18mm$, the cleaning tool will be shifted in y-axis (perpendicular to the pipe) a distance d_y with value $d_y > 20mm$, which is above the system tolerance.

V. OUR APPROACH

The problem of centering the robot is that any of its six wheeled-legs may be extending over a corrosion with size up to 40*mm*, influencing its alignment to the pipe's center.

Previously, from figure 6, the extreme cases of eccentricities were presented, in which the bottom wheeled-legs of the maintenance unit were extended to the pipe radius size, over one and two imperfections.

The proposed centering approach starts by extending the wheeled-legs to the maximum value as if all wheeled-legs were stepping over the maximum corrosion size, this is $l = r - 40mm$. After this, the legs continue extending until all make contact to the pipe. However, if the equally extended wheeled-legs are extended to a certain value under the pipe radius, it can be concluded that the robot is not centered. And the question to answer is, **how to decide to which direction relocate the robot's maintenance unit to be centered?**. Consequently, additional sensor information is required to compute the direction for the adjustment.

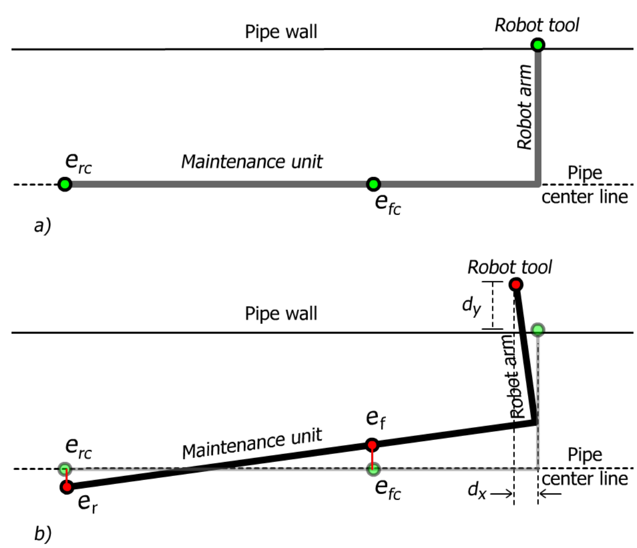

Fig. 7. Maintenance unit - wire model in cross-section lateral view, showing how the eccentricities from the rear e_r and the front e_f wheeled-legs influence the position of the robot and the its tool. a) Maintenance unit perfectly center to the pipe, no eccentricities, $e_{rc} = e_{fc} = 0$. The robot tool is on the surface of the pipe wall and perpendicular to the pipe center line. b) Maintenance unit with eccentricities on rear e_r and front e_f wheeled-legs, creating a shifted distance d_x for the robot tool in the x-axis (pipe's horizontal) and a shifted distance d_y in the y-axis from the pipe center.

A. Centering process

If we are able to include a sensor or sensors for measuring the corrosion height from the pipe wall, then the centering process will be solved. This type of sensors, such as Hall sensors, must be mounted on the wheeled-legs. However, the measures from the sensors may be inconsistent, as the corrosions are often incrusted inside the pipe.

According to the structure and functionality of the robot,

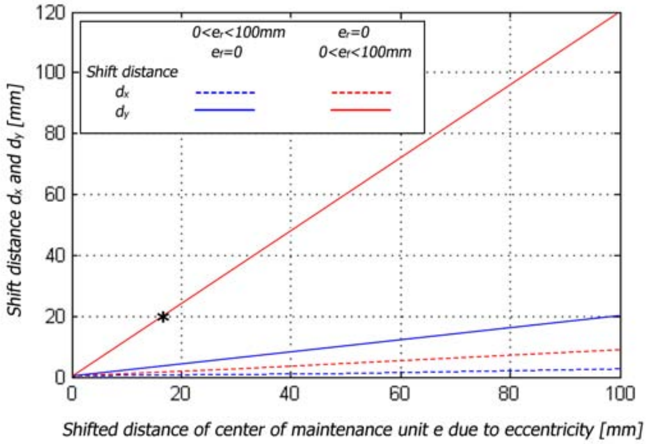

Fig. 8. Influence of eccentricities e_f and e_r on shifted distance d_x and d_y. a) Shifted distance when e_f is fixed and e_r is varied from 0 to $100mm$, revealing a maximum $d_x = 6mm$ when $e_f = 100mm$ and $e_r = 0$. b) Shifted distance when e_r is fixed and e_f is varied from 0 to $100mm$, revealing a maximum $d_y = 120mm$ when $e_f = 100mm$ and $e_r = 0$. $*$ is the tolerance point.

the optimal solution is to add a measuring sensor on the tool system - drive wheel, in this way we are able to read the measures on the pipe surface from a known position of the robot while rotating. In other words, the absolute measurement system read the distances from the current position of the robot to the pipe surface while the cleaning/sealing tool is rotating around the pipe.

Initially, the set of wheeled-legs are extended to an arbitrary distance. Then, the tool system rotates one revolution clockwise, and the measurement data is collected from a linear potentiometer integrated into the drive wheel of the tool. Once the system finishes one rotation and the data is collected, a fitting circle algorithm calculates the radius and the center coordinates of the fitted circle. In this way, it is possible to determine the eccentricity e of the center of the maintenance unit from samples of measurements around the pipe as shown in figure 9. Finally, the set of front wheeled-legs (L_1, L_2 and L_3) are able to its position and reach the center of the pipe within the tolerances.

Circle Fitting: Circle fitting as well as the fitting of various geometries is a common problem in application areas like computer graphics, statistics and coordinate metrology [18]. Some research in circle fitting without a unified approach started in 1960, but it wasn't until 1990 when the growing computer science community realized the problem of fitting simple contours as a fundamental task in computer vision and pattern recognition [19]. Since then many new algorithms have appeared. Our circle fitting problem can be defined as to find the circle that best fits a collection of points $\{(x_i, y_i)|3 \leq i \leq N\}$ in the plane $\mathbb{R}2$ and a minimum of three point are needed.

A circle is mathematically defined as the set of points (x,y) that fulfills following equation $(x-a)^2 + (y-b)^2 = r^2$ or in parametric form $x = a + r\sin(t)$, $y = b + r\sin(t)$, where (a,b) are the coordinates of the circle center and r is the radius.

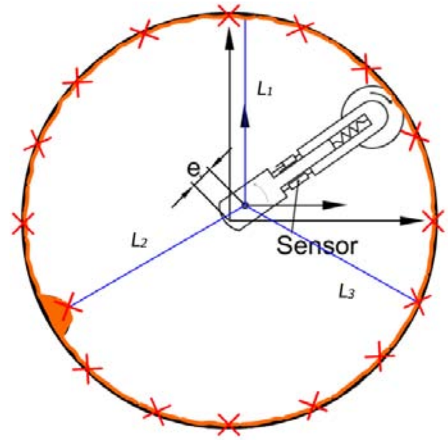

Fig. 9. The absolute centering system includes a potentiometer on the tool system - drive wheel to map the geometry of the inner pipe wall in order to apply a circle fitting algorithm and reposition the robot to the center of the pipe.

A circle can also be described by an algebraic equations with the following general form $A(x^2+y^2)+Bx+Cy+D=0$ where the coefficients, A, B, C and D are algebraic parameters. All circle descriptions mentioned before are equivalent to each other. The natural parameters a, b, r can be expressed in terms of the algebraic parameters:

$$a = -\frac{B}{2A}, b = -\frac{C}{2A}, R^2 = -\frac{B^2 + C^2 - 4AD}{4A} \quad (1)$$

The problem of circle fitting is to find the coefficients a, b and r or A, B, C and D that best fit the given data. For this particular problem the algebraic circle fitting is selected instead the geometrical, due to its simplicity to be implemented in small micro-controllers. In specific, we selected the Taubin's [20] method which improves Kasa [21] by being resistant against underestimating the circle radius for non uniform distributed data.

We denote $z_i = x_i^2 + y_i^2$ for brevity. Taubin proposed a fitting algorithm which is to minimize the function

$$F_t = \frac{\sum_{i=1}^{n}[Az_i^2 + Bx_i^2 + Cy_i^2 + D]^2}{n^{-1}\sum_{i=1}^{n}[4A^2 z_i + 4ABx_i + 4ACy_i + B^2 + C^2]^2} \quad (2)$$

where the constrain is $\sum_{i=1}^{n}[4A^2 z_i + 4ABx_i + 4ACy_i + B^2 + C^2]^2 = 1$. In our application, we collect $n = 10$ points from the surface of the inner pipe, which is sufficient to resolve A, B, C, D by minimizing Taubin's function (equation 2). Due to (1), one can compute the center coordinates (a, b) of the fitted circle.

VI. EXPERIMENTS

For evaluating the robot centering process, a smaller robot was constructed in order to test the fitting algorithm in our laboratory. This smaller robot, mimics the DeWaLoP maintenance unit, consists of six wheeled-legs, including one linear actuator on each leg with feedback potentiometer and a push button representing the force sensor of the real robot, as shown in figure 11. In addition, this smaller version of

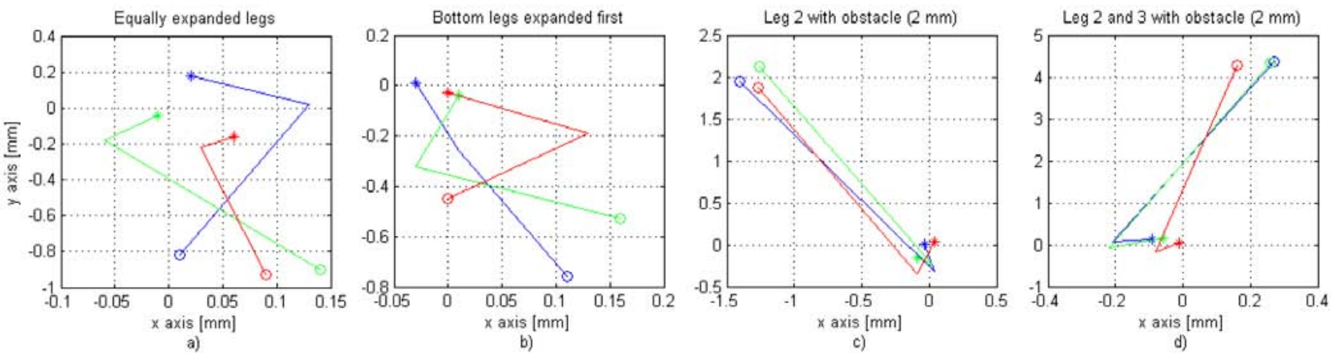

Fig. 10. Absolute centering approach when initial condition are: a) All legs are equally extended to the pipe radius in a perfect pipe with no corrosion. b) The bottom legs are first extended to the pipe radius and after the top leg in a perfect pipe with no corrosion. c) Similar to case *b* but with an offset of 2*mm* on one of the bottom legs. d) Similar to case *b* but with two offset of 2*mm* at each bottom legs. The measurements and the repositions were performed three times represented in each figure in blue, green and red. The '*o*' in every figure shows the initial position of the robot before applying the circle fitting and the '$*$' shows the final position after the circle fitting algorithm has been applied. (Cases *a* and *b* are presented to compare the initial and final position of the robot in a ground truth basis, where the pipe is free of corrosion.)

the maintenance unit, integrates a linear potentiometer on its single tool arm, in order to gather data for the fitting algorithm.

This small prototype of the robot is 1:20 scale of the real robot. In this way, the maximum corrosion thickness will be 2*mm* representing the 40*mm* in reality.

For the centering method, the Taubin's circle fitting algorithm calculates the center coordinates of a circle from ten samples of points uniformly distributed across the inner - circumference.

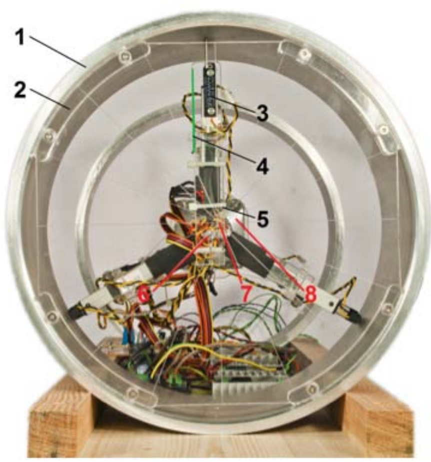

Fig. 11. DeWaLoP prototype. 1) Pipe. 2) Acrylic master plate with center position. 3) Linear potentiometer. 4) Position reference for the rotatory arm (mimicking the DeWaLoP tool system). 5) Rotatory arm. 6) Prototype center. 7) Pipe center. 8) Motor for rotatory arm.

The experiment was conducted as follows:

Initially, the robot was in compressed mode, and the maintenance unit is laying on its bottom legs over the inner pipe surface. In this way, the initial position of the robot is not centered.

Step 1. Extend the legs.

The legs were extended from its compressed position in four different ways.

I. The wheeled-legs were equally extended to the pipe radius within a perfect pipe.

II. The bottom legs were initially extended to the pipe radius inside a perfect pipe, and then the top leg was extended.

III. One of the bottom legs was stepping over the 2*mm* corrosion.

IV. The two bottom legs were stepping over 2*mm* corrosion. The center position of the maintenance unit (3 wheeled-legs) after extending the legs of these four cases are shown in figure $10a,b,c$ and d, respectively.

Step 2. Collect the measurement data.

Once the maintenance unit extended all its legs, the tool system rotates clockwise (as seen from the front). At each rotation interval of 36°, the robot read measurement data from the linear potentiometer mounted on the tool system, which is contacting the pipe surface. Ten location coordinates of the tool system were obtained, which means ten points of pipe surface were measured.

Step 3. Centering process.

The robot CPU calculated the fitting circle algorithm with the ten points collected.The the robot repositioned.

Step 4. Verification of the centering process.

The system measures again the ten points, by rotating the tool system at each 36° interval. From figure 10, the '$*$' marks the final position of the center of the maintenance unit after the circle fitting algorithm applied.

In general the repositioning method performed the centering process of the robot as expected, reaching the result of maximum e_f of 0.1*mm* in the prototype scale. This is equivalent to $e_f = 2mm$ in really, which is under the eccentricity tolerance (18*mm* as we analyzed in previous section).

VII. CONCLUSIONS

This paper presents the analysis and solution of centering an in-pipe robot when corrosion structures stochastically influence its position. By centering an in-pipe robot, the rotating tools (cleaning and sealing) are able to revolve around the pipe from its central axis without the need of adjustment. In this way, the tools perform optimally while protecting itself from hitting the pipe.

To center the robot in the pipe, we add a potentiometer which is able to compress or extend on the tool system of the robot. While the tool system is rotating on the inner surface of the pipe, multiple surface point data are collected. In order to obtain the non-circular geometry of the inner pipe, we apply a circle fitting algorithm to reposition the robot to the center of the pipe.

For the experimental results, a smaller DeWaLoP robot was constructed, to test in laboratory scales. The results showed good repeatability from different initial cases where the robot was eccentric to the pipe.

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