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Design of a robot for in-pipe inspection using omnidirectional wheels and active stabilization

Edwin Dertien[1], Mohammad Mozaffari Foumashi[1], Kees Pulles[2] and Stefano Stramigioli[1]

***Abstract*— This paper discusses the design of a vehicle for in-pipe inspection using omnidirectional wheels and active stabilizing control. A novel propulsion mechanism is discussed using omnidirectional wheels (or omni-wheels) is presented which allows direct control of the orientation in the pipe. This paper will show the development and evaluation of a prototype model. Rapid prototyping techniques have been used in this proof-of-principle.**

I. INTRODUCTION

The PIRATE (Pipe Inspection Robot for Autonomous Exploration) project aims at developing a robot platform for in-pipe inspection of the low pressure (urban) gas distribution mains. The platform has to be able to carry out visual inspection and leak searching using auditive noise-based sensors. Based on statistical data available on the (Dutch) gas distribution net [12], design requirements for size and maneuverability have been determined [9].

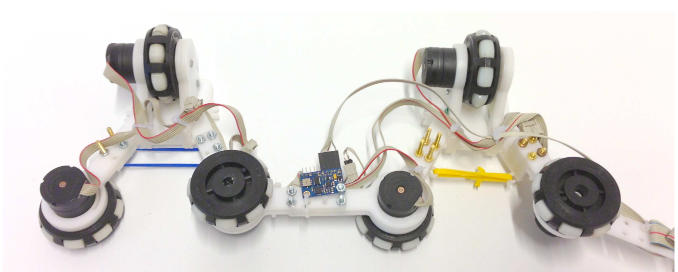

Fig. 1: Robot design with two clamping V-shapes using omnidirectional wheels

A. Goal

One of the most restricting design requirements is being capable in maneuvering in smooth PVC and PE pipes (also occasionally in grey cast iron) in a relatively wide diameter range of 63 mm (57 mm inside) to 125 mm while at the same time being able to take a sharp (mitered) bend. In earlier work [2] a mechanism has been presented satisfying these requirements. In order to make an axial rotation in the pipe however a series of clamping and unclamping motions is necessary, as shown in video of this work [1]. In this paper a solution will be presented which allows for continuous control of the axial orientation of the mechanism, while clamping inside the pipe.

B. State of the art

Many very different designs exist for mechanisms moving inside pipes. In the category of *wheeled* inspection vehicles (as opposed to crawling snake-like robots [14] or pneumatic inch-worm type mechanisms [5]) a distinction can be made between clamping mechanisms and non-clamping. A different branch of magnetic wheels [15], tailored for moving only in ferro-magnetic pipes is not considered here. For inspection of large sewer pipes a large number of wheeled vehicles exist which provide traction with the pipe-wall simply trough their weight. In smoother pipes a way of clamping the vehicle is necessary for maintaining traction force. A number of wheeled clamping structures exist, all with their own merits considering minimal pass-trough, number of clamping contact points and number of articulated joints, moving inside pipes such as the MRINSPECT series [3] and the advanced work on the CMU Explorer series [14] and many others starting with the work by Hirose et al. [4]. Recently a number of overview articles of in-pipe inspection robots have been published such as the work by Roslin et al. [10] or Liu et al. [6]. However, none of the existing projects targets both the small diameter, large spreading factor and capabilities of taking mitered bends at the same time.

C. Robot concept

The chosen concept: a clamping V-shape has been discussed briefly in the works by Neubauer et al. [7]. The conceptual design of the RoboScan [13] and the PIRATE series of in-pipe inspection robots [2][9] make use of this concept. The PIRATE concept is shown in figure 2 and consists of two clamping V-shapes separated with a module for axial rotation. Note that the robot can move both in the horizontal and vertical plane (and anywhere in between) aided by this rotation module. The preferred driving orientation will be in the horizontal plane, so most of the pictures and schematic drawings in fact show the *top view*.

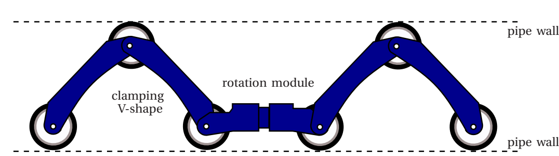

Fig. 2: Schematic overview of the original robot concept

[1]Robotics and Mechatronics group, CTIT Institute, University of Twente, 7500 AE Enschede, The Netherlands e.dertien@utwente.nl
[2]Kees Pulles is with Kiwa, Apeldoorn, the Netherlands kees.pulles@kiwa.nl

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D. Proposed mechanism

With most of the peristaltic or crawler-type robots no attention is paid to the orientation (or rotation) of the system inside the pipe - or is not actively compensated for. The CMU snake [14] makes explicit use of the rotation movement inside a pipe and compensates the generated CCTV image so the operator has a level horizon view. Other systems such as the MRINSPECT or Roboscan design have a preferred orientation but can change their orientation also by a series of (un)clamping and rotation movements.

The chosen curved shape of the PIRATE robot modules enforces a preferred orientation for taking bends and corners, i.e., they can only be taken in one plane or orientation, dictated by the direction of the bend. One of the prerequisites of taking a corner is that this orientation or rotation in the pipe can be selected or controlled. In the original PIRATE design this is facilitated by a separate rotation module which allows one section of the robot to unclamp and rotate with respect to another module which stays clamped.

In the conceptual Roboscan design [13] this rotation is possible by rotating the driven wheels around their z-axis. However, in the limited space available for the PIRATE concept, there is no room for extra actuators.

The rotation using a rotation module whilst clamping one of the modules causes an amount of friction of the module that is rotating in the pipe, as can be seen in de video's [2]. An alternative has been found in using smooth plastic (nylon) wheels instead of the rubber wheels, but in the second prototype with all-wheel-drive this solution was no longer an option.

A possible solution for this problem is explored in this paper, using **omni-wheels**[1] or mecanum wheels[2]. These wheels have been used in many robot platforms mainly aimed at a flat floor. They have been deployed in other pipe inspection robots, such as commercially exploited by helical robotics [3]. One reference of using omni-directional tracks in the context of pipe inspection had been found in the works of Tadakuma et al.[11].

Fig. 3: Transwheel image - *image from Kornylak.com*

In the following section the analysis of the design considerations will be given, followed by implementation details, results and conclusions.

II. ANALYSIS

In this section the main considerations for adapting the previous design will be given, focusing on the clamping mechanism, the propulsion, sensing and modularity. The realized robot is shown in figure 1 for reference. The implementation of this design will be discussed in the next section.

The clamping V-shape used in the previously described robot needs to unclamp before a rotation in the pipe can be made, as described in [2]. This clamping and unclamping is realized using a series of pre-programmed movements (basically unclamp-rotate-clamp).

A. Orientation

Due to irregularities in the pipe surface, weight distribution, pulling of the tether the robot will not remain in the chosen plain, but its orientation can deviate over time. Periodically unclamping, rotating and re-clamping is so far the only possible solution. For semi-autonomous control, used by an operator, this behavior is highly undesirable.

A mechanism needs to be found without a holonomic constraint around systems principle axis, so that continuous control of the mechanisms orientation is possible. Although eventually autonomous control is intended with the mechanism, also for user controlled operation this mechanism would be desirable, especially since selection of entering bends and T-Joints is depending on the orientation of the system.

For forward propulsion, traction (resistive force or friction) in the driving direction has to be maximized by the wheels. The chosen wheels have small inset wheels consisting of rubber.

However, for the rotation maneuver, it is necessary that the robot has as little friction with the pipe wall as possible. In the first prototype this has eventually been solved by replacing most of the rubber wheels by nylon wheels. The same problem has been solved on a different (conceptual) level by the RoboScan design [13] where wheels have been employed which can rotate round a vertical axis. This concept has also been used in many other designs described by [10]. The solution explored and proposed here makes use of the properties of an omniwheel to provide friction necessary for traction in the driving direction while allowing free motion in a direction tangential to the wheel.

B. Wheel choice

Robots with omnidirectional wheels are mainly used on flat floors. Different wheel designs exist, the main difference lying in their *roll-off shape*. A typical mecanum wheel can have a continuous motion on a flat floor providing traction perpendicular to the roller wheel orientation, for example 45∘. In the chosen wheel the roller wheels are perpendicular to the driving direction. On flat floors normally a double set of these wheels is used, however

[1]WikiPedia on OmniWheels

[2]Sometimes also called 'Swedish wheels'. The wheels used are called 'Transwheel' by Kornylak.com

[3]Helical Robotics website: http://www.helicalrobotics.com

space constraints only allow for one. The number of roller wheels used inside one omniwheel influence the 'bumpiness' of the rolling motion.

C. Clamping

The robot uses a V-shaped section consisting of two modules to generate friction force with the wheels for traction. The amount of friction force that can be generated using this V-shape is depending on the diameter of the pipe. The maximum attainable clamping force (F_n) on the pipe wall is given by (repeated from [2]):

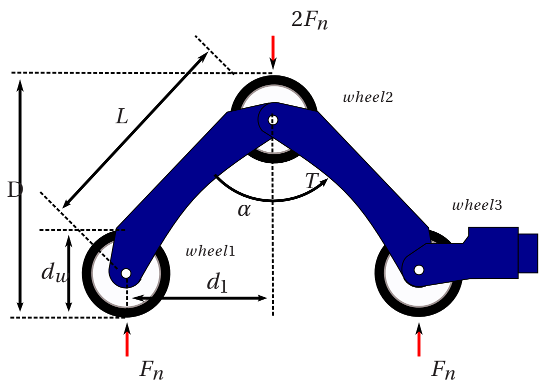

Fig. 4: Schematic view of a clamping V-shape. Note that the center wheel has been drawn in driving direction in this figure.

$$F_n = \frac{T}{d_1} = \frac{T}{\sqrt{L^2 - (D - d_w)^2}} \tag{1}$$

where L is the length of a module, d_w is the wheel diameter, D the pipe diameter and T the exerted torque by the clamping module (see figure 4). The relation is graphed in figure 5 with $L = 0.075\ m$ and $d_w = 0.052\ m$. The wheel diameters are considered identical for all wheels in this case. Since the mechanism is ideally operating in the horizontal plane (all the schematic drawings show the *top view* of the system) gravity does not directly counter-act the clamping force graphed in figure 4.

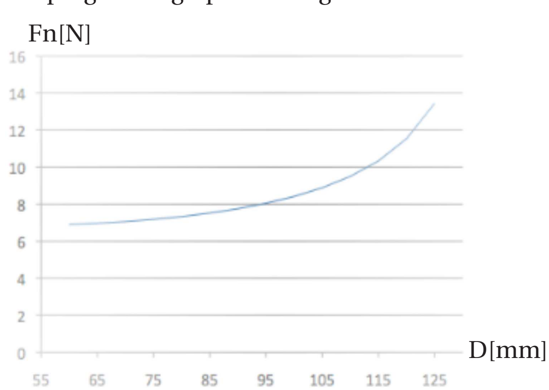

Fig. 5: Normal force on the pipe wall per Nm clamping torque for different pipe diameters

The reaction torque of the wheels used for propulsion also add to clamping torque T, depending on the driving direction. In forward direction the torque of the second drive motor adds to the clamping torque while first and third motor subtract from the effect.

$$T = T_{clamp} + T_{motor2} - T_{motor1} - T_{motor3} \tag{2}$$

In the previous prototype the clamping torque is generated through a DC motor using a worm gear. Power of this motor is transferred to the joint trough a spring (series elastic[8]) and worm gear which enables the joint to keep a clamping force without powering the motor, even compensating for small bumps in the pipe wall without any intervention.

For simplicity sake the clamping force has been provided using a linear spring (implemented as a series of rubber bands). To keep the robot centered in a 125mm pipe a clamping force of at least 5N needs to be provided (experimentally validated). The force provided by the joint in this pipe is 13.5 N per Nm according to figure 5. A torque of $5/13.5 = 0.37Nm$ is necessary, which can easily provided using the chosen rubber bands.

Although the deformation of the roller wheels due to hysteresis in the material is very small, it still causes a considerable amount of rolling friction F_{rf}, depending on the exerted amount of clamping force. To let the robot drive (uphill) a traction force of at least 4.41N has to be delivered by three motors (from results of the measurements on the previous robot prototype), resulting in 100 mNm per motor. The force loss

$$F_{rf} = C_r \cdot F_n = \frac{C_r}{\mu} \frac{T_m}{r_w} \tag{3}$$

is depending on wheel radius r_w and estimated friction constant $C_r = 0.01 - 0.015$. The resulting friction torque is about 5% of the motor torque per wheel.

The chosen motors (Faulhaber 2619 SR series with included 112:1 gear box) can deliver up to 100mNm. Due to space restrictions these where the only motors available capable of delivering the required torque without additional gear reduction.

The wheel motors have 16 ppr incremental encoders on the motor shaft. With a reduction of 1:112 and a wheel diameter of 52 mm this results in a resolution of 0.083 mm per pulse which is more than sufficient for velocity measurement and position control.

D. Active Stabilization

For the active stabilization a straightforward PID controller will be used. Since odometry data is likely to be influenced by slip with the pipe wall, an external sensor for orientation is necessary. An accelerometer will be used. An accelerometer measures gravitation but also external accelerations (and can not distinguish between both).

Since the accelerations in z-direction or y-direction (tangent to the pipe wall) are minimal with respect to the main drive motion in x-direction, acceleration data of the y axis provides the most reliable source while driving in the horizontal plane. Note that when driving in the vertical plane also the z axis is necessary to yield an accurate and high-resolution signal. The angle can be calculated using

$$\phi = arcsin(a_y)$$

where a_y is the digitally acquired acceleration in y direction (tangent to the pipe wall).

III. IMPLEMENTATION

A. Mechanical design

In order to quickly evaluate the design and test the stabilization control a mechanical prototype has been designed using flat 3 mm Delrin sheet and a limited number of extra parts. Using flat plate has the advantage that the design can be manufactured quickly using a laser cutter, allowing for short development cycles. The CAD design is shown in figure 6, the final implementation in figure 7. In totally stretched configuration the robot is 47 cm long and weighs 450 gram.

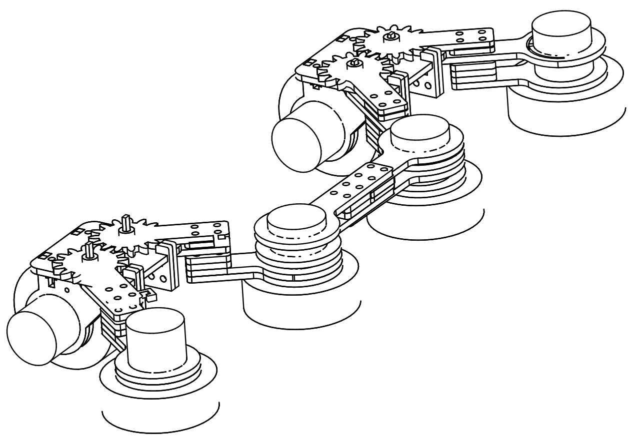

Fig. 6: CAD sketch of the proposed robot mechanism

The design uses six motorized wheels using the earlier described Faulhaber 2619 SR series with included 112:1 gear box. The omni-wheels have been mounted to the output shafts directly.

In order to keep the orientation of the rotation motor perpendicular to the pipe wall, the joint in the clamping V-shape consists of two geared branches. The gears make sure the piece holding the rotation motor always holds the center of the triangle. The both legs of the triangle have a length of 75 mm, the wheels have a diameter of 52mm. In theory a range of diameters between 80mm and 125 mm should be possible using this setup, where it not for the size (length) of the motors. Only when they are mounted inside the wheels (the 52 mm wheel allows for a 26 mm motor to be mounted within) this minimum diameter can be ranged using this prototype.

As described in the previous section, instead of the active clamping mechanism for this prototype a passive system is used. The rubber bands extended 86mm inside the pipe with the diameter of 125 mm. The force exerted from the rubber bands when the module is inside a pipe with the diameter of 120 mm is between 7.0 N and 7.2 N (measured by a spring balance).

Fig. 7: Model inside a 125mm pipe

B. Electronics

Control electronics for the experiments consist of an embedded micro controller (Atmel ATmega328) controlling the DC motors through a number of H-bridge driver chips (L298) measuring current through shunt resistors and low-pass filter. Two incremental encoders, one on a drive motor and one of a rotation motor have been connected for measuring position. Lastly an ADXL345 accelerometer shown in figure 8 has been connected through an I^2C bus for measuring orientation.

Since for the time being only one rotation is considered (and allowed by the setup) just one axis of the accelerometer has been used, using $\phi = arcsin(a_y)$ as value for the angle. Note that this axis is the most accurate to use for deviations in the horizontal plane.

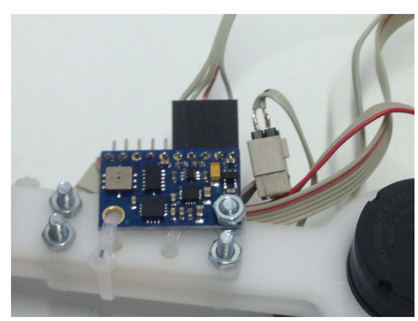

Fig. 8: Accelerometer on a multi-sensor interface board mounted centrally in the mechanism

C. User interface

The user interface has been kept to a bare minimum for this proof-of-principle. An analog joystick has been connected to the control electronics, where one of the axes gives the control set point for the linear motors (the four drive-motors) and the other axis gives the set point to the rotational motors (the two motors tangent to the pipe axis) as an offset for the stabilization control.

D. Active stabilization

A PID controller has been used to control the robot's orientation. Since damping in the system due to friction is very high and the first-order behavior is dominant, the D action can be omitted. The velocity of the rotation motor can be controlled (PWM controls voltage, for a running motor which can be seen as a pure gyrator) equivalent to the velocity) while position (orientation) is measured. Hence the encoder acts as a 'hidden' integrator. Instead of deriving a velocity signal (with the possible added noise by adding a differentiator) the choice has been made just to use the controller with position feedback and a reasonably large feedback gain.

As stated in the introduction, goal of this work is not to design an optimal controller for the discussed prototype, rather than have a working proof-of-principle in order to investigate possibilities.

All data (timestamp, set points, motor current, accelerometer data and encoder data) has been outputted serially at 50Hz and is shown in the graphs in the next section.

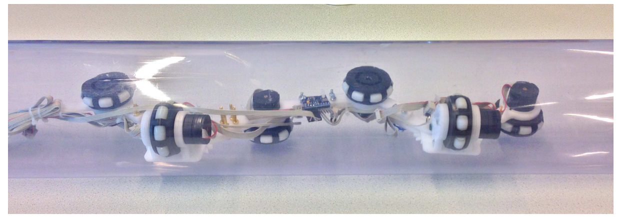

Fig. 9: Robot in a 125 mm transparant pipe

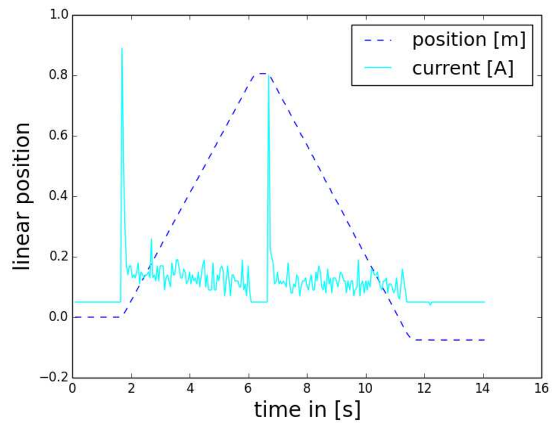

Fig. 10: Straight drive with minimal disturbance, translation of the robot including total motor current

IV. RESULTS

The clamping force of passive clamping mechanism has been tested using spring balance and digital scales. The force exerted by the passive spring equals 7.2 N inside the 125mm pipe. Experiments show that this is enough force for traction but still slip occurs in both translation as rotational direction. Three tests in short 125mm diameter pipe segments are described here. The robot mechanism drives trough a straight section clear acrylic pipe with minimal disturbance, followed by a test drive in a straight section with a large disturbance. In the last test a bend with a large (4D) radius has been used.

A. Straight section

The robot is entered in the pipe drives 80 cm forward and back. Figure 9 shows the experimental setup. Figure 10 and figure 11 show the measurement data obtained in this drive. The forward velocity is quite high compared with previous prototypes: $0.8m/4sec = 0.20m/s$. The accelerometer data shows a lot of noise. These might be contributed to the uneven surface of the wheels caused by the individual rollers. The deviation between the encoder data (purple) and the accelerometer data (green) is caused by the slip of the roller wheels.

In a next experiment two times a large disturbance of 90° is introduced by rolling the pipe with the robot over the table (shown in 12 at t=4.5s and t=8s) . This is of course a disturbance highly unlikely to occur in real life, however, it shows the capability for quick recovery of the system. The results are shown in figure 12.

Finally a test run has been made in a bend in 125mm pipe with a radius of 4D shown in figure 13. As to be expected, for this range the mechanism does not behave any differently from driving in the straight pipe. However, rotation becomes more difficult since the mechanism has a preferred orientation.

V. CONCLUSIONS

This paper presents a novel design for a pipe inspection robot using omnidirectional wheels with active balancing control. This setup allows for a very intuitive mapping to user control (rotation and translation in the pipe) which is its main benefit compared with earlier prototypes which had to relay of a series of clamping and unclamping motions in order to conduct an axial rotation in a pipe. A proof of principle setup has shown the possibilities of the control, as well as maneuvering in a straight 120mm pipe and a smooth bend with a radius of 4D. Experiments have been done with the outline of the robot and the positioning of the wheels finding the most suitable distribution of contact points.

In the presented prototype the active clamping mechanism has been omitted for sake of simplicity, but this mechanism has been implemented in earlier work and will have to be incorporated in the following model. This will be a necessary step to conduct and verify the capabilities of the earlier prototype, being inclinations, sharper bends and a right-angle T-junction.

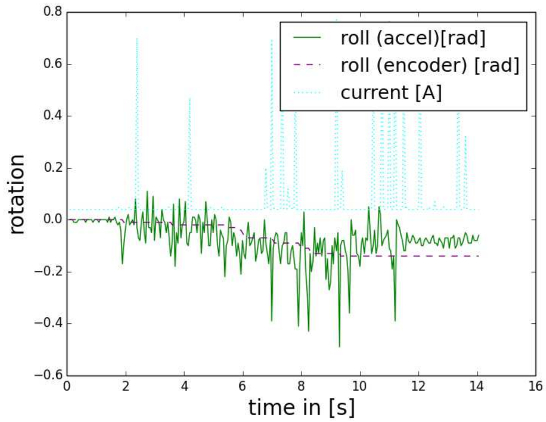

Fig. 11: Straight drive with minimal disturbance, rotation of the robot

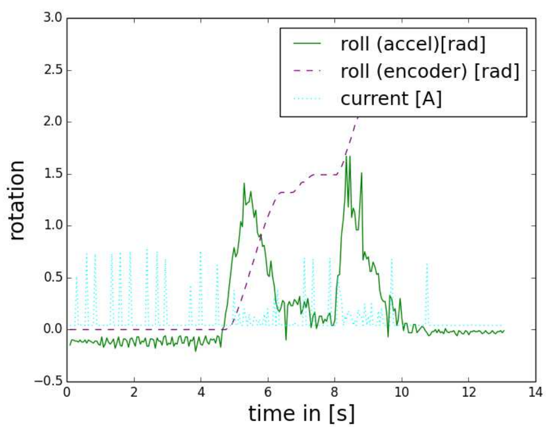

Fig. 12: Rotation in a 125mm pipe with two large disturbances

ACKNOWLEDGMENT

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REFERENCES

[1] E. Dertien and S. Stramigioli. Basic maneuvers for an inspection robot for small diameter gas distribution mains. In *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, pages 3447–3448, 2011.

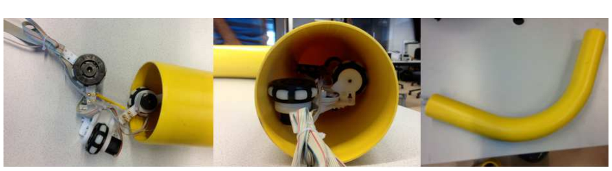

Fig. 13: Robot concept in 125 mm bend with radius of 4D

[2] E. Dertien, S. Stramigioli, and K. Pulles. Development of an inspection robot for small diameter gas distribution mains. In *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, pages 5044–5049, 2011.

[3] Se gon Roh and Hyouk Ryeol Choi. Differential-drive in-pipe robot for differential-drive in-pipe robot for moving inside urban gas pipelines. *IEEE TRANSACTIONS ON ROBOTICS,*, 21(1), 2005.

[4] Shigeo Hirose, Hidetaka Ohno, Takeo Mitsui, and Kiichi Suyama. Design of in-pipe inspection vehicles for φ25, φ50, φ150 pipes. In *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, volume 3, pages 2309–2314. IEEE, 1999.

[5] Ho Moon Kim, Jung Seok Suh, Yun Seok Choi, Tran Duc Trong, Hyungpil Moon, Jachoon Koo, Sungmoo Ryew, and Hyouk Ryeol Choi. An in-pipe robot with multi-axial differential gear mechanism. In *Robotics and Automation, 2013. Proceedings. ICRA '13. 2013 IEEE International Conference on*, 2013.

[6] Zheng Liu and Yehuda Kleiner. State of the art review of inspection technologies for condition assessment of water pipes. *Measurement*, 46(1):1 – 15, 2013.

[7] W. Neubauer. A spider-like robot that climbs vertically in ducts or pipes. In *Intelligent Robots and Systems '94. 'Advanced Robotic Systems and the Real World', IROS '94. Proceedings of the IEEE/RSJ/GI International Conference on*, volume 2, pages 1178–1185 vol.2, 1994.

[8] G.A. Pratt and M.M. Williamson. Series elastic actuators. In *Intelligent Robots and Systems 95. 'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on*, volume 1, pages 399–406 vol.1, 1995.

[9] C. Pulles, E. C. Dertien, H. J. van de Pol, and R. Nispeling. Pirate, the development of an autonomous gas distribution system inspection robot. In *International Gas union Research Conference, IGRC 2008, Paris, France*, USA, October 2008. Curan Associates.

[10] Nur Shahida Roslin, Adzly Anuar, Muhammad Fairuz Abdul Jalal, and Khairul Salleh Mohamed Sahari. A review: Hybrid locomotion of in-pipe inspection robot. *Procedia Engineering*, 41(0):1456 – 1462, 2012. <ce:title>International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012)</ce:title>.

[11] K. Tadakuma, R. Tadakuma, Keiji Nagatani, Kazuya Yoshida, S. Peters, Martin Udengaard, and K. Iagnemma. Crawler vehicle with circular cross-section unit to realize sideways motion. In *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*, pages 2422–2428, 2008.

[12] Pieter van Vollenhoven. Gasexplosie na breuk van gasdistributieleiding. Technical report, Raad voor de transportveiligheid, 2002.

[13] George C. Vradis and William Leary. Development of an inspection platform and a suite of sensors for assessing corrosion and mechanical damage on unpiggable transmission mains. Technical report, Foster Miller, March 2004.

[14] C. Wright, Austin Buchan, B. Brown, J. Geist, M. Schwerin, D. Rollinson, Matthew Tesch, and H. Choset. Design and architecture of the unified modular snake robot. In *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, pages 4347–4354, 2012.

[15] E. Zwicker, W. Zesch, and R. Moser. A modular inspection robot platform for power plant applications. In *Applied Robotics for the Power Industry (CARPI), 2010 1st International Conference on*, pages 1–6, 2010.