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Pirate, the development of an autonomous gas distribution system inspection robot

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1. ABSTRACT

A consortium of four companies is developing an autonomous inspection system for small diameter, low pressure gas distribution mains.
Such a system could eventually replace the current practice of leak survey and improve the assessment of the quality of the mains, being able to investigate the mains from the inside and very closely.
A complete system consisting of small robotic platforms, docking stations for battery recharging and data communication, and entrance locks is envisioned.
The logistics of such a system seem feasible, although the technological challenge is daunting.
Besides the development cost the other major parameter determining the cost of the system is the allowed maximum distance between docking stations.
Preliminary analysis of the business case show that a robotic platform driving at a speed of 0.2 km/h and an availability of 50% would earn 160 000 € annually, being the value of its inspection results. This justifies a serious attempt for further evaluation of the vision.

The consortium.
As a start Kiwa Gastec Technology, a company specialized on technical consultancy for gas distribution, contacted three partners for realising the initial stage of the system: Continuon, a major LDC in The Netherlands, for financing the project and consultant for all hands-on experience managing a gas distribution system. Demcon, as a specialist in high-tech mechatronic systems and IMPACT, the Institute of Mechanics, Processes, and Control of the University of Twente, for its experience on robotic design and locomotion.
Together they took upon the task to design and build a robotic platform, able to navigate though small pipes with T-joints and elbows and potentially robust enough for use in the gas distribution grid.

The robot
In the period of one year a robot was designed and built with precisely those properties. The robot is shown in the figure. A promotional video can be seen at www.ce.utwente.nl/e13/pirate.

The robot is constructed of seven segments. It is propelled by two driving wheels, driven by small electric motors with gear transmission. Friction for traction is ensured with two actuators for bending the first segment relative to the second (and the last segment relative to the previous). Sensors for torque and angle are situated inside the wheels.
In order to choose the desired direction through T-joints, as well for general steering, the middle segment contains a rotation joint, which enables to rotate one halve of the robot relative to the other halve.

The high level control of the robot is situated in the electronics segment of the robot. All electronics fit on a printed circuit board of 40 x 30 mm, the maximum size that fits into the allotted space.
The total weight of the robot is approximately 1200 grams.

The future

Building the robot is a crucial step, but only the first step on a long road towards a complete system. In the immediate future the robot will be tested for durability, manoeuvrability and power consumption.
The robot will be augmented with a miniature CMOS camera and LED for visual inspection and a (ultrasonic) microphone for leak detection. It will be tested on small missions (limited in distance and time) under field condition and used for demonstration purposes.
New funding will be required to for further development. With this funding the sensors and software for orientation and localizations will be developed. The other components of the complete inspection system as well as more thorough evaluation and testing of the robot is planned for an even later stage.

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C O N T E N T S

2. DESIGN CONSIDERATIONS OF THE INSPECTION SYSTEM

2.1. The business case

The benefits of any activity should be weighed against its costs. In the case of an autonomous inspection system for gas distribution lines the benefits are potentially threefold:

1. Savings from the current leak survey costs
2. Lower incident and accident costs
3. Lower mains replacement cost

Ad 1. The current manual leak survey cost about 1 man-hour pro kilometre, including overhead. Assuming a man hour cost of 40 € and an inspection interval of 1x per 5 years, the potential benefits are 8 €/(km yr).

Ad 2. The gas distribution system is already very safe. During the last 10 years there have been about 16 accidents in The Netherlands involving "component defect" according to the accident registration data. No fatalities occurred, although there were some serious injuries. If we assume that all those accidents could have been prevented with a suitable inspection system and assume an average incident cost of about 150 k€ and a grid length of 120 000 km, we calculate the potential benefits at 2 €/(km yr).

Ad 3. The potential savings in replacement costs are under most circumstances the major driving factor for the development of the system. The uncertainty in the savings is, however, even larger than for the previous two items. If we assume that the usual replacement rate of 1%/yr can be reduced to 0.8% per year, and assume the replacement cost to be 100 k€/km, the saving are 200 €/(km yr). A reduction of 20% may seem far fetched, but one has to regard the amount of pipes that are nowadays decommissioned because of their uncertain quality, whilst afterward they appear to be still in perfectly acceptable condition.

As a ball park estimate and with the considerations of the preceding paragraph we state that the potential financial benefits of an inspection system would be of the order of 100 €/(km yr). Is this enough to cover the costs?

We assume the availability of an inspection tool like an mostly autonomous robot equipped with suitable sensors. Typically such a tool would move with a speed of 0.04 m/s, have an availability of 50% and a lifespan of 5 years. It could thus inspect 3500 km in it lifetime. Using the above ball park estimate the value of its measurements would be 350 000 €.

We guess that the production of such a robot and sensors and its operational costs can be realized for less, so that a viable business case exists. There is thus a compelling argument to initialize research in this direction.

2.2. The ultimate inspection system

It is illustrative to considerer the ultimate inspection system in term of consequences for the gas distribution. The hardware of such a system would probably consists of 4 different components:

1. The robot platforms, perhaps in different versions, each with their specialized sensors
2. The recharging station (data and energy)
3. The entrance lock for the platforms
4. A command and data analysis centre

For the low pressure gas grid in The Netherlands, with a length of about 100 000 km we arrive at the following characteristics:

Assumptions:

Average inspection frequency	1x per 5 yr	
Robot platform incl. sensors:	Life span 5 yr,	cost 20 000 €, recharging 1x /day, maintenance 1x /yr
Recharging stations:	Life span 10 yr,	cost 1 000 €
Entrance lock	Life span 30 yr,	cost 3 000 €
Command centre (hardware only)	Life span 5 yr,	cost 20 000 €

The total size of the system would be:

30 robots,	replacement rate 6 /yr,	cost 120 000 €/yr
10 000 recharging stations	replacement rate 1000 /yr,	cost 1 000 000 €/yr
150 entrance locks,	replacement rate 5 /yr,	cost 15 000 €/yr
2 command centre (1 backup)	replacement rate 0.4 /yr,	cost 8 000 €/yr

Two immediate conclusions can be drawn from this simple analysis:

a) The numbers and costs are manageable, logistically as well as financially
b) The robot range is a major factor that determines the system cost. The maintenance cost of the inspection system is almost inversely proportional with the distance between two recharge points.

2.3. Robot specifications

An exhaustive list of requirements for the autonomous pipeline inspection robot is surprisingly large. We limit ourselves therefore to the requirements that are specific for its use in an underground gas piping system. We also identify the important compromises made early in the design process, in order to keep the project feasible.

a) Environment: Size. The robot should be able to drive trough the majority of the mains. Based on an inventory of some typical Dutch gas distribution grids a range of inner diameters from 57 mm to 114 mm was selected. Extension if this range, particularly to larger diameters is desirable but was deemed to pose to big a challenge
b) Environment: Manoeuvrability. The robot should be able to navigate through elbows (90^o, $r={}^1/_2D$) and T-joints in all directions and take slopes op to 30^o (the initial target of 45^o was reduced as later calculated indicated that this would compromise the robot speed too much)
c) Environmental conditions. The robot should operate in natural gas ($0 < P < 200$ mbarg) of low (zero) humidity and it should be able to negotiate bumps (but fusion rills) and pipe surface materials as PE, PVC and cast iron, and a certain amount of sand and tar. It was accepted that worst case conditions of amount of sand, tar or water might block the passage for the robot.
d) Propulsion and actuation of the robot should be done by battery. Although other means have been discussed, they were rejected as too impractical or to costly in terms of development time (or both).
e) Mission length. Although the business case indicates the need for an almost indefinite mission, an absolute minimum of 30 min was identified for the first prototype design.
f) Power consumption. There is no explicit maximum specified; power consumption is implicitly limited by the amount of available (battery and motor)space and the desired duration of mission and robot range
g) Communication (internal). The robot will use “smart” sensors, motors and actuators. A wired bus system is needed for sending commands between the main controller and those components. The choice for a specific communication bus will also put constraints

on the integrated circuits for the design. On basis of the estimated data transfer (control loop speed), the restrictions on space and on the complexity of the protocol the I2C (also known as TWI) bus system is chosen

h) Communication (external). The communication with the robot to the outside world is recognized as a potential bottleneck and even as a show stopper when no adequate solution can be provided. Nevertheless, it was decided very early in the design process not yet to spent effect on this issue. This decision was motivated by the argument that new telecommunication principles and protocols (consider e.g UWB, Bluetooth, wireless USB), are still being developed and improved. And a second argument is that sophisticated, or even just wireless, communication is not an absolute requirement for a first step demonstration prototype. Even with a simple cable interface a lot can be learned and demonstrated.

3. THE DESIGN OF THE ROBOT

A literature compilation was already done by another member of the PIRATE team (E. Dertien [3]) and the references can be found in the references of this article. Many reports from research institutes and universities have been studied, but there were actually only 2 reports on inspection robots that provided useful information for this project. Those are the ExplorerII (developed at Carnegie-Mellon University [2]) and RoboScan (developed by Foster-Miller ,Inc. [4]). But both of these research projects are based on moving through pipes of a much larger diameter than the smallest diameter in the PIRATE project, so many ideas and techniques from these research projects were not directly applicable.

The concept is based on the Roboscan design, but with some major changes to make it suitable for small diameters. It consists of 7 modules and 8 wheels. A module in this case is the body between two wheels and the functional parts within. The wheel axles are also the rotation axes for the modules. This way all the degrees of freedom (DOF) between the modules are in one plane. Module 1 and 2 form one drive unit and module 6 and 7 form one drive unit. Two drive units are the minimum for this robot, because one drive unit will loose traction when passing through a mitered bend (elbow/sharp 90^{o} corner). The normal driving plane of the robot will be the horizontal plane, in order to avoid driving through dirt (water, oil, tar, etc.) in the lower section of the pipe. When driving horizontally, the robot can also easily enter small diameter side branches.

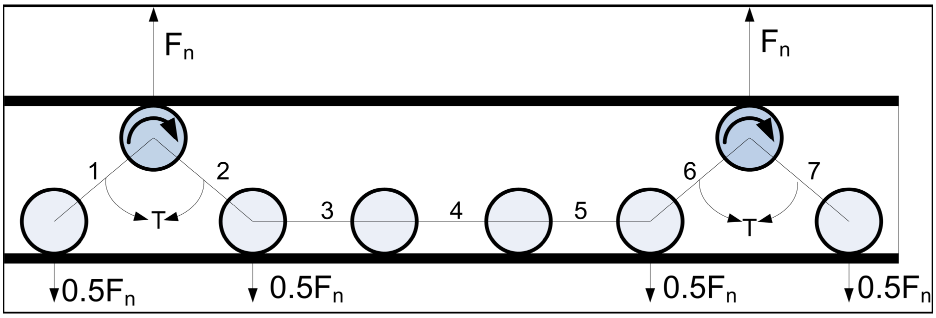


Fig. 1 Basic design and lay-out of the robot segments.

The first and the last module in the chain are the drive modules, They contain an electro motor for propulsion of the robot. Module 2 and 6 are the bending modules. They can actuate the in-plane rotational DOF of the modules connected to it. Module 3 and 5 are payload modules, they contain the batteries and the main electronics for the control of the robot. The axle-axle distance of the wheels plus the wheel diameter has to be more than 119 mm in order to be able to drive in a pipe of the largest diameter as well. Because the modules need to be this long and also fit through a pipe of the smallest diameter, they need to have an asymmetric shape. The modules have a 'banana' shape, see figure 3.6.

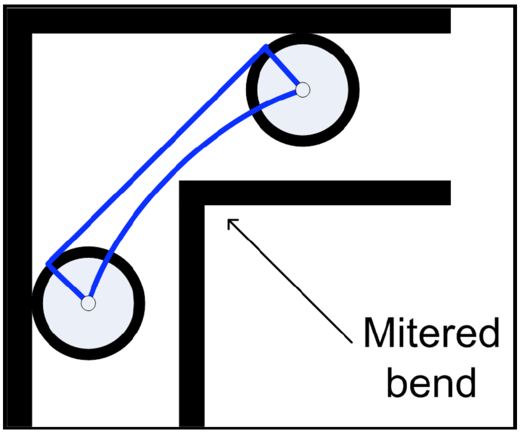


Fig. 2 Minimum available space for the robot segment.

In order to go both left and right, the robot needs to rotate itself around the pipe centreline. Module 4 has an extra internal rotational degree of freedom to enable this. By using module 4 to rotate the first three modules relative to the other three modules, the robot is able to rotate in the pipe.

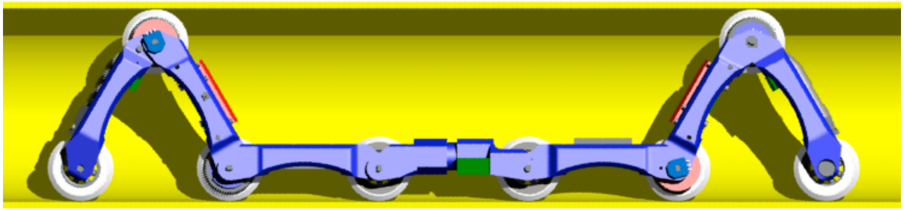
The robot needs seven actuators (two drive actuators, four bending actuators and one rotation actuator). The challenge is to fit all those actuators in the robot. Module 2 contains actuators to set the angle between module 1 and 2 and also between 2 and 3. Module 6 does the same for module 5 and 6 and for module 6 and 7. The angles between module 3 and 4 and between 4 and 5 are not actuated; they contain only a spring to keep them in their neutral position. The actuated angles contain an actuator in combination with a spring, so the position actuator changes to a torque actuator. It is necessary to have a torque actuator, because the torque between the modules creates normal force on each of the wheels.

Alternative designs have also been investigated (see Lit. 25), but for a variety of reasons and weighting the specifications of 2.3 this design is selected as the most viable one.

4. THE PROTOTYPE OF THE ROBOT

The total robot was modelled in 3D in Solidworks. As many parts were to be produced on regular non-CAD based production machinery, drawings had to be created for all the parts. All these drawings were directly created from the 3D model.

As the prototype is most appreciated when showing it in its intended environment we present here the drawing from the simulation (see Lit. 25]).



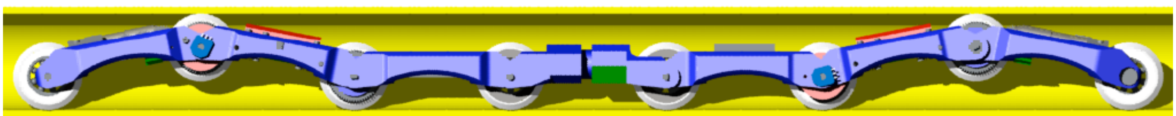


Fig. 3 The shape of the robot in the minimum and maximum diameter pipe.

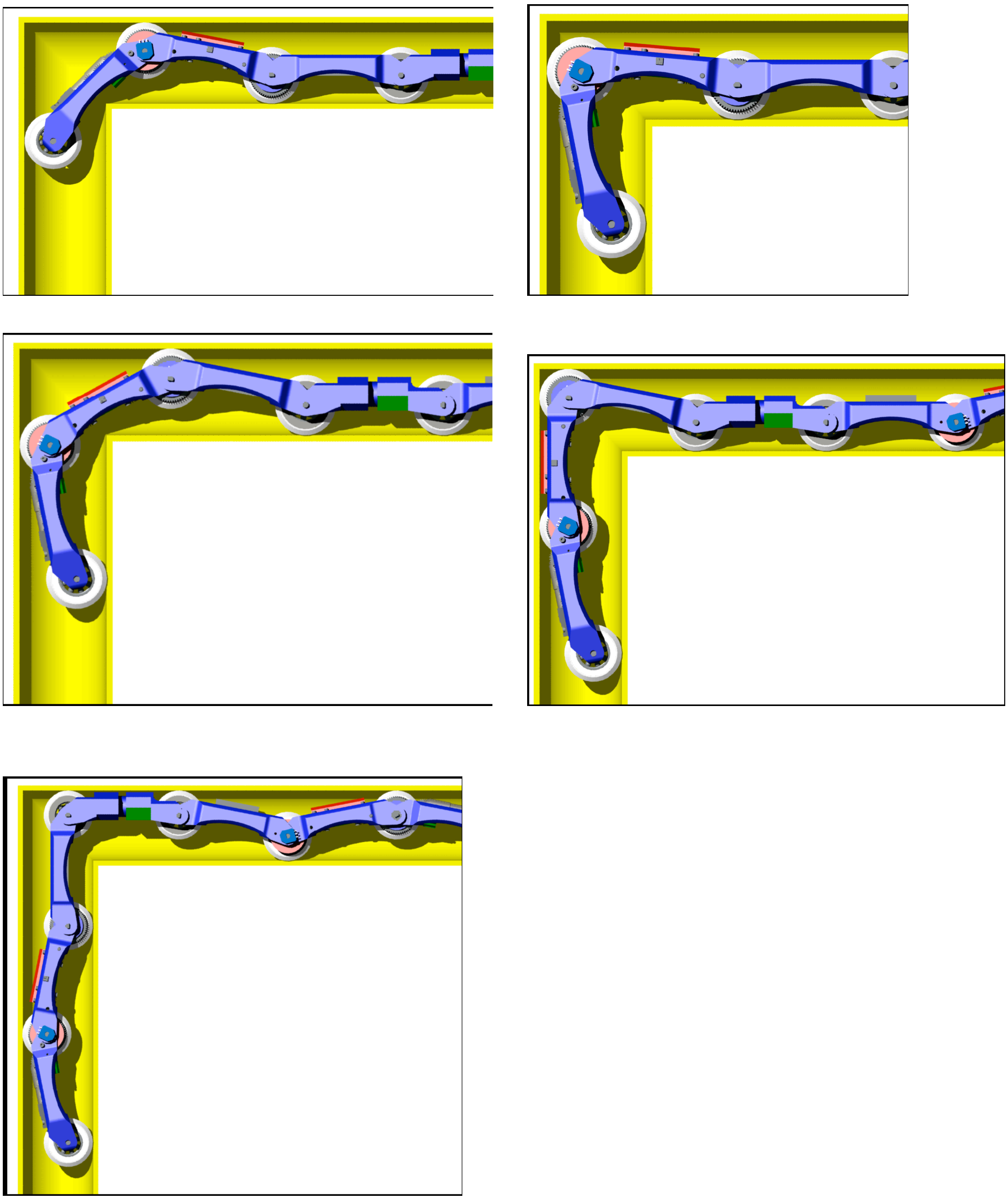


Fig. 4 Navigating through a right angle bend in five stages.

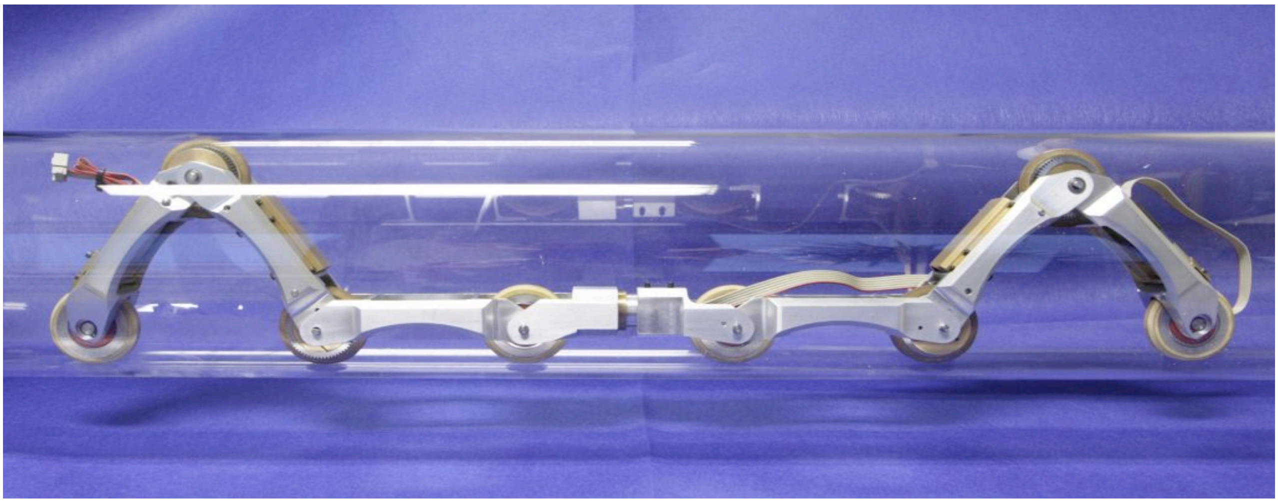


Fig. 5 The robot Pirate inside its designated territory: the 63 mm main, transparent version.

5. CONCLUSION

5.1. Results

The robot is now in it prototype stage. The lessons learned form the design and build phase are:

- The business case for an autonomous gas distribution mains inspection system is promising
- A segmented robot appears to be the most efficient design
- The size of the robot and the components needed are about the smallest that can be manufactured with conventional techniques
- Manufacturing tolerances need to be watched and tightly controlled
- Energy consumption of the robot and the storage of energy will be an important bottleneck operating the robot. These limitations will greatly influence the design, logistics and ultimately performance of the complete inspection system
- Constructing the robot of this small size is very challenging, but it can be done with a dedicated and competent team in about 18 months.

5.2. Next phase

The future of the system depends on the availability of new funding. The majorl LDC's in The Netherlands have showed serious interest in participating in the furter development of the inspection system. The immediate next steps are

- the development of software for autonomous navigation through bends ant joints.
- performance and endurance tests of the robot in a test circuit. The test circuit is already build and available at the premises of Kiwa Apeldoorn.

6. REFERENCES

Lit. 1 Kees Pulles, Concept Voorstel Demonstratiesysteem robotinspectie voor gasdistributie, InterneMemo, 12 mei 2006.

Lit. 2 CMU, *Explorer-II:Wireless Self-powered Visual and NDE Robotic Inspection System for Live Gas Distribution Mains*, CMU Robotics Institute, 31 January 2006.

Lit. 3 Foster-Miller, *Development of an Inspection Platform and a Suite of Sensors for Assessing Corrosion and Mechanical Damage on Unpiggable Transmission Mains*, NGA and Foster-Miller,March 2004.

Lit. 4 Carlson, J. and R. R. Murphy, *Reliability Analysis ofMobile Robots*, Proc. of the 2003 IEEE conference on Robotics an Automation, Taiwan 2003.

Lit. 5 Dertien, E.C. ,*Literatuurstudie Autonome LeidingInspectierobots*, intern rapport, Universiteit Twente, 2006.

Lit. 6 Stancliff, S., Dolan, J. and Trebi-Ollennu, A., *Towards a Predictive Model of Mobile Robot Reliability*, CMU-RI-TR-05-38, August 2005

Lit. 7 Pulles, K., *Programma van eisen robotinspectie gasdistributieleidingen*, interne memo, KIWA Gastec, 2 juni 2006.

Lit. 8 nternet,*http://www.itrobotics.com*, company website, 2006

Lit. 9 Pulles, K., *Energie uit de gasstroom* Interne memo, 22-6 2006

Lit. 10 Isidor Buchmann *What is the perfect battery?* www.buchmann.ca, April 2001

Lit. 11 Differential-Drive In-Pipe Robot for Moving Inside Urban Gas Pipelines Se-gon Roh and Hyouk Ryeol Choi, Member, IEEE, 2005

Lit. 12 A Micro Snake-like Robot for Small Pipe Inspection, Shuichi WMMOTO, Jun NAKAJIM, Masanori TAKATA, Takefumi KANDA and Koichi SUZWOR, Okayama University, 2003 INTERNATIONAL SYMPOSIUM ON MICROMECHATRONICS AND HUMAN SCIENCE

Lit. 13 Control Circuit in an In-Pipe Wireless Micro Inspection Robot Kazuhiro TSURUTA, Takanari SASAYA, Takayuki ShYBATP. and Nobuaki KAWAHARA 2000 INTERNATIONAL SYMPOSIUM ON MICROMECHATRONICS AND HUMAN SCIENCE

Lit. 14 Development of Autonomous Mobile Microrobot Shin-ichiro KAWAKITA, Research Laboratories, DENSO CORPORATION

Lit. 15 Micro Inspection Robot for 1-in Pipes, Koichi Suzumori, Member, IEEE, Toyomi Miyagawa, Masanobu Kimura, and Yukihisa Hasegawa IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 4, NO. 3, SEPTEMBER 1999 -

Lit. 16 A simple architecture for in-pipe inspection robots, M.HORODINCA, I.DOROFTEI, E.MIGNON & A.PREUMONT, Int. Colloquium on Mobile and Autonomous Systems, IFF, Magdeburd, June 25-26, 2002

Lit. 17 Control Design of an Electro Pneumatic Micro Actuator for a Mobile In Pipe Micro Robot Cédric Anthierens, Mecatronics'01, Besançon (France) - October 9-11, 2001

Lit. 18 Control and Guidance of a Pipe Inspection Crawler (PIC) Majid. M. Moghaddam1, and Alireza. Hadi2 22nd International Symposium on Automation and Robotics in Construction ISARC 2005 - September 11-14, 2005, Ferrara (Italy)

Lit. 19 Design of In-Pipe Inspection Vehicles for 25, 50, 150 Pipes Shigeo Hirose, Hidetaka Ohno, Takeo Mitsui, and Kiichi Suyama :,Proc. ICRA, Detroit, pp.2309-2314 (1999)

Lit. 20 Experiences with the development of a robot for smart multisensoric pipe inspection H.-B. Kuntze* and H. Haffner** Proceedings of the 1998 IEEE International Conference on Robotics& Automation, Leuven, Belgium l May 1998

Lit. 21 Development of an Inspection Platform and a Suite of Sensors for Assessing Corrosion and Mechanical Damage on Unpiggable Transmission Mains Dr. George C. Vradis Consultant to the RD&D Director, NYSEARCH / Northeast Gas Association, Final Report October 2002 – March 2004

Lit. 22 Miniature pipe robots Zengxi Pan and Zhenqi ZhuThe authors Department of Mechanical Engineering, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, 2001

Lit. 23 Multiconfigurable Inspection Robots for Low Diameter Canalizations E.Gambao, M. Hernando and A. Brunete 22nd International Symposium on Automation and Robotics in Construction ISARC 2005 - September 11-14, 2005, Ferrara (Italy)

Lit. 24 Design of PIRATE Mainboard Edwin Dertien Control Laboratory University of Twente, the Netherlands September 28, 2007

Lit. 25 Development of a pipe inspection robot, J.J.G. Vennegoor op Nijhuis, University of Twente report WA-1096. may 2007

Lit. 26 Electronic design for a gas pipe inspection robot, J. Ansink, Internal report Control Engineering Mechatronics, Faculty of EWI University of Twente

7. LIST TABLES

8. LIST OF FIGURES