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Advances in Development and Testing of a System of Autonomous Inspection Robots for Drinking Water Distribution Systems

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ABSTRACT

An aging network in combination with stricter stakeholder requirements force the Dutch drinking water sector to improve the asset management of their water transport and distribution networks. Autonomous inspection robots (AIRs) provide a means to obtain knowledge on the condition of more pipes against lower cost, resulting in more focused rehabilitations and replacements, reduction of water loss through leakage, and a better knowledge and understanding of the system. In 2017, the Dutch water utilities started a joint product development project together with KWR and 4 technology providers with the aim of developing a system of autonomous inspection robots that is ready for implementation in an operational setting. In our contribution to the 2017 CCWI conference, we presented the concept and startup of the development. In this contribution, we report on the progress which has been made since. We start by reiterating the need for more advanced inspection technologies for aging drinking water infrastructure such as autonomous inspection robots. Then, we briefly describe the background and recent progress in the development of the system. We present a business case approach to justify the development and application of the robot system. Finally, we describe the testing facility which is under development for AIR.

Keywords: inspection, robotics, testing

1 Introduction

An aging network in combination with stricter stakeholder requirements force the Dutch drinking water sector to improve the asset management of their water transport and distribution networks. Pipeline inspection is an important aspect of improved asset management programs, and serves the following purposes:

1. supporting pipeline replacement decisions for individual pipes, to prevent destruction of capital due to replacing pipes that are in good condition;
2. supporting long-term planning of investments in the drinking water infrastructure, by increasing knowledge of the condition of both individual pipes and pipe cohorts;
3. verifying the exact location of water distribution assets, as well as their characteristics;
4. finding leaks to reduce water losses.

Although the relevance of pipeline inspection is understood and accepted, high costs, hygienic risks and nuisance to the environment currently prevent the water utilities from applying pipeline inspection on a large scale. Therefore, asset management of the drinking water transport and distribution system is currently based on generic knowledge and models of pipe cohorts, supplemented with inspection data for only a limited number of pipes. High inspection costs, hygienic risk, and environmental nuisance are mainly caused by the insertion and extraction of inspection tools that are nowadays inherently part of pipeline inspection. Autonomous inspection robots (AIRs) provide a means to keep tools in the network for a longer time, thereby significantly reducing the number of insertions and extractions. In this way it becomes possible to obtain knowledge on the condition of the majority of pipes within the acceptable pipe diameter range for the robot system (in our case 100-300 mm). This results in more focused rehabilitations and replacements, reduction of water loss through leakage, and a better knowledge and understanding of the system. In addition to this, robots may contribute to improved water quality monitoring. This, as well as the vision described in the next sections, was already described by [1], but is reiterated here to set the context.

2 Vision

Drinking water networks are complex pressurized underground networks with many bends, branches, diameter changes and material changes. They are typically situated in a built environment, and they are intendedly inaccessible in order to reduce the risk of contamination. Because of these characteristics, the drinking water transport and distribution networks are very distinct from other pipe systems in which condition assessments are performed. In order to meet all the specific requirements which come with this special nature, an inspection concept is proposed that is different from all approaches that are currently applied: a system of autonomously operating robots (AIRs, autonomous inspection robots) that "live" in the network and are fitted with several sensors for condition assessment of pipe walls and other purposes (Figure 1).

3 Current state of development

A consortium of four technology providers, seven water utilities and one research institute has been formed to develop the robot system:

- Demcon (mechatronics and lead developer);
- DoBots (autonomy);
- Acquaint (pipe inspection and sensoring);
- Geodan (geo-information systems);
- Brabant Water, Dunea, Evides, PWN, Vitens, WMD, WML (end users: water utilities);
- KWR Watercycle research institute (organizational and testing hub).

The first phase of product development has been completed, in which solutions have been devised and tested for all critical functions which had initially been identified as technological risks for the development project. Because of considerations with respect to intellectual property, the technical details are not shared here.

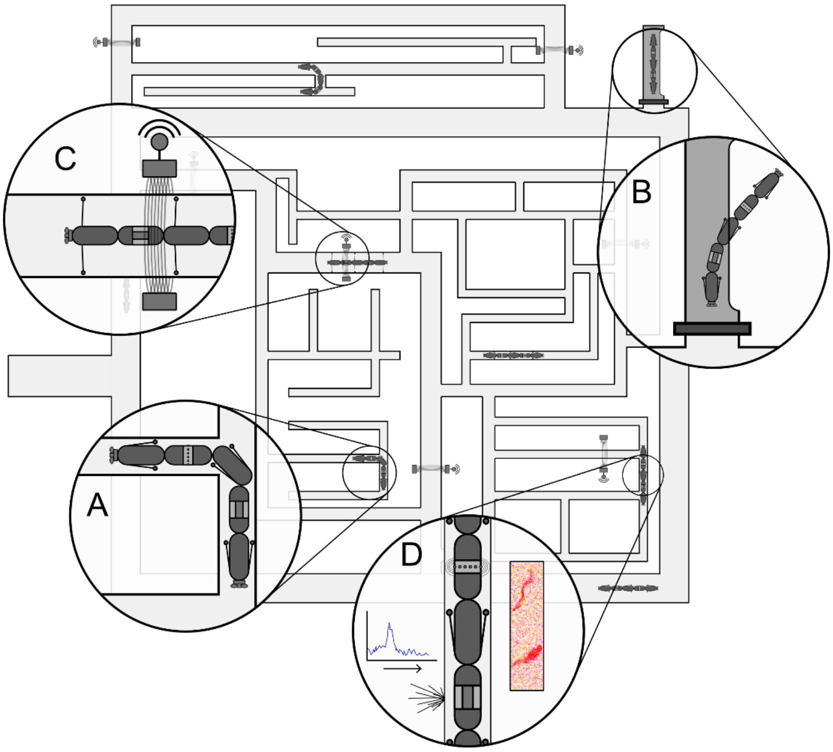

Figure 1: Vision of a system of autonomous robots that can freely move through the network (A), with access points for maintenance (B), facilities for energy and data transfer at several locations in the network (C), that is fitted with relevant sensors for pipe condition assessment, leak detection, etc. From [1].

4 Business case

4.1 Description

The decision to initiate and continue the development of the AIR system has been supported by an elaborate business case study. This has initially been set up for the Dutch utilities as a group, and was then refined in two rounds for individual water utilities.

4.2 Methodology

This section does not describe the business case calculation in its full detail for lack of space, but provides a sufficiently detailed overview to understand its merits and drawbacks. Table 1 gives an overview of the costs that have been considered and the way they have been calculated. Table 2 does the same for the benefits. All factors are considered at their appropriate times in a time window starting at the start of the development process, through the start of the introduction of the robot system in networks, to the end of life of the system. This includes replacement of all components at appropriate times (in accordance with their expected life). After the completion of the development of the system, it is assumed that the introduction of the system and the reaping of its full benefits ramps up over a number of year from 0 to its full potential. Both for the costs and the benefits, the Net Present Value is calculated. These values are combined to compute a return on investment factor RoI by dividing the latter by the former.

In order to test the sensitivity of the RoI for assumptions in the business case calculations, scenarios in which one or more of the cost categories are assumed to be underestimated (real values 150% or

Table 1: Overview of costs.

	category	*components*	*determination of costs*
a	system development	development costs	calculation by technology suppliers
b	frame of reference for localization	measuring of reference points	reference point density * length of inspectable pipes * unit measuring price
c	infrastructure	entry/exit points	point density * length of inspectable pipes * (unit point price + installation costs)
		base stations	base station density * length of inspectable pipes * (unit station price + installation costs)
d	robots	purchase costs	inspection frequency * length of inspectable pipes / effective number of km inspected per unit time * robot unit price
		maintenance costs	number of robots * estimated person hours for maintenance * hourly rate
e	additional costs	data handling	company specific estimate
		recuperation costs	number of robots * failure rate * unit recuperation costs
		base station maintenance costs	company specific estimate

Table 2: Overview of benefits.

	category	*components*	*determination of benefits*
1	leakage reduction	leakage reduction	technical leakage rate * estimate of achievable reduction * water production * marginal water production costs
2	reduction of failures	for 3 network cohorts	failure frequency * total length of pipes in this cohort * estimated achievable reduction * costs per failure
3	prevention of early replacement	for 3 network cohorts and 3 material classes	difference of current replacement costs and NPV of postponed replacement costs with appropriate interest rate and life extension of: annual replacement rate * length of pipe in cohort * fraction which is replaced proactively * fraction of this which is replaced >10 years before technical end of life * 4replacement costs per unit length
4	reduction of customer minutes lost + other benefits	reduction of customer minutes lost	number of failures * estimated achievable reduction in failure rate * CML per failure * costs per CML
		others	company specific estimate

200% of estimated values) and/or one or more benefit categories are assumed to be overestimated (real values 50% of estimated values).

4.3 Illustrative results

This section shows illustrative results which do not reflect the actual relevant numbers for the water utilities in the consortium. Input values are fictitious and generally of the same order of magnitude as the real numbers for the utilities but significantly different. Nevertheless, the results illustrate the approach and sensitivity analysis. The nominal scenario shows a *RoI*>>1 (upper left corner of Figure 2). For scenarios in which one or two cost categories have been underestimated and/or one or two benefit categories have been overestimated, we still get a *RoI*>1 (yellow symbols in Figure 2). The business case brakes down for a smaller number of scenarios with multiple over- and/or underestimations (red symbols in Figure 2).

4.4 Conclusions for the Dutch utilities

For each of the seven water utilities, the business case was found to be strongly positive, but to a varying degree. This relates to different network compositions, leakage rates, marginal costs for water production, and estimates of achievable improvements. It was also found to be quite robust to cost underestimations and benefit overestimations. As better estimates for several parameters in the business case calculations become available during the development process, the business case calculations are updated in each phase of the project.

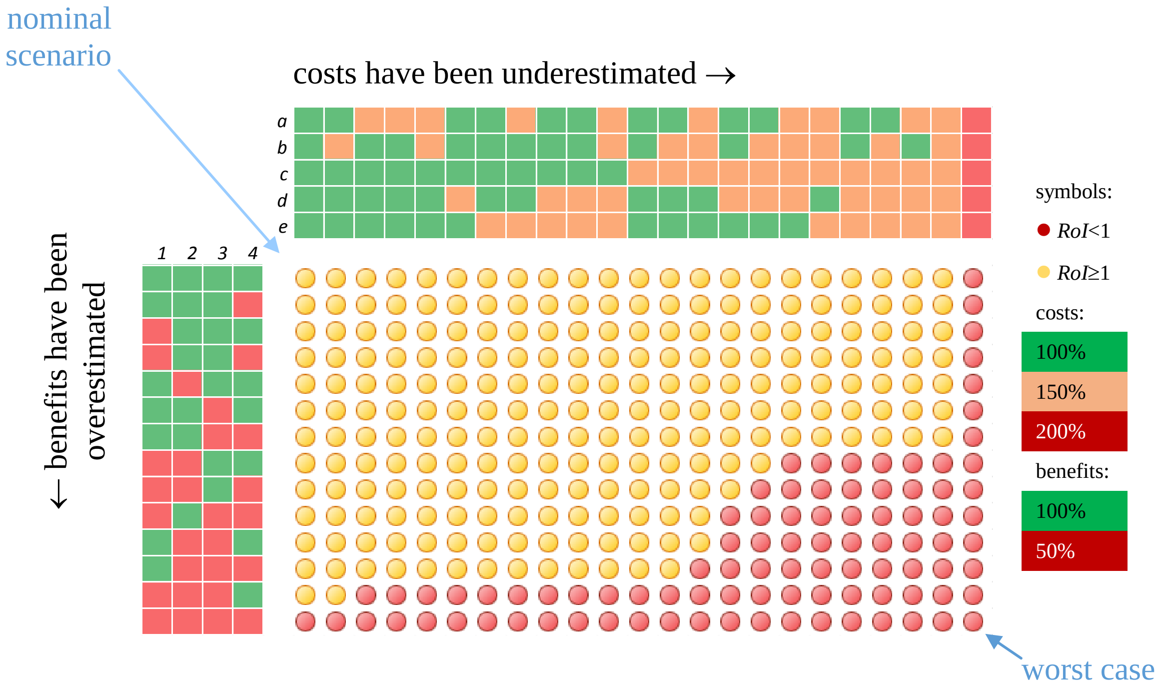

Figure 2: Sensitivity analysis of the business case. Letters a-e and numbers 1-4 refer to cost and benefit categories in Table 1 and Table 2, respectively.

5 Testing and commissioning environment

5.1 Introduction

An essential component for the robot system development project is a safe network in which robots can be trained and tested and fail without negative consequences for customers or the need to open up a life network. In order to meet these needs, a testing network is being developed and constructed at KWR. Is has been designed to present all difficulties and challenges to the robot which the real networks will also present it. As such, it can be used to train the robot how to deal with these challenges, and to demonstrate that the robot is actually safe to introduce into a buried network.

5.2 Requirements

An overview of the requirements which have been defined for the training and testing environment is given in Table 3. These include requirements on materials, bends, joints, special conditions, the water and the installation itself. Also, a number of components/aspects which are out of specification for the robot system have been included. The robot will have to be able to deal with these situations in practice as well.

5.3 Design and realization

The design which has been made on the basis of these specifications is shown in Figure 3. The network includes many valves and hydrants and also multiple locations in which pipes can easily be replaced for different, materials, diameters and old or degraded pipes. Preparations for the construction of the system are underway. We aim to finish the construction process by the end of the year.

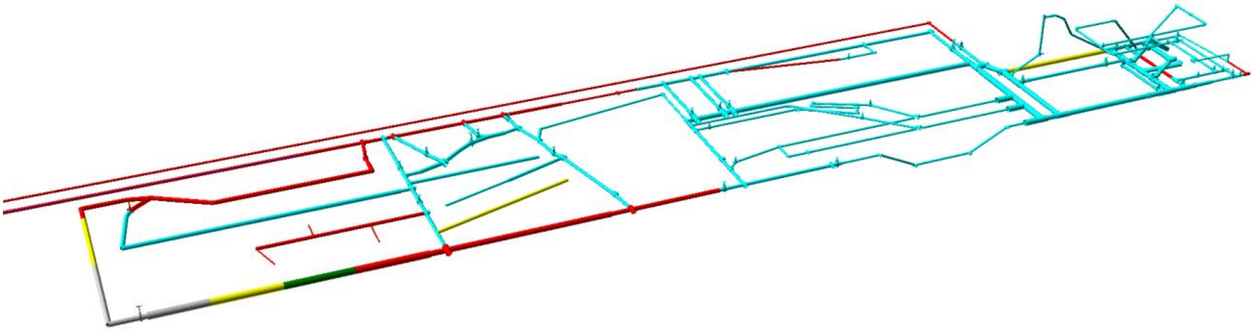

Figure 3: Overview of the test network design. The rightmost part of the network will be inside a building, in which also the pumps and tank will be situated. The width of the image corresponds to about 60 meters. The pipes running towards the left edge of the image continue for another 50 meters, where they connect. Pipe colors: cyan: PVC; red: PE; yellow: cement coated cast iron; grey: steel; green: fiberglass reinforced plastic.

6 Conclusions and outlook

The development of a system of autonomous inspection robots for drinking water networks is progressing quite well. The business case for such a system is (very) positive for a large part of parameter space for all participating utilities. A testing environment has been designed and is

Table 3: Overview of testing environment requirements. Note that these contain aspects that are out of specification for the robot system itself.

Category	*requirements, in spec*	*requirements, out of spec*
Materials	PVC, PE, AC proxy, cement coated CI, cement coated DI, PE-alu, steel material transitions aging, corrosion, degradation, biofilm	other materials small section of transparent pipe
pipes, bends, joints	100-300 mm nominal diameter horizontal bends in all available angles vertical bends up to 45 degrees (3xD bending radius) horizontal T, Y joints 100-200 m straight pipe successions of bends range of pipe lengths between bends extreme diameter transitions specific repair constructions all relevant joint connections	<100 mm, >300 mm nominal diameter vertical bend > 45 degrees succession of vertical bends together > 45 degrees vertical T-joint
network components	gate valves, butterfly valves, hydrants, tappings	
special conditions	leakage differential settlements pipe cracks and deformation tree roots ‘All known and common pipe network exceptions’	
water	1-10 bars 0-2 m/s (2 m/s up to 160 mm pipes) control on air bubbles, sediment, free floating biofilm, turbidity, water hardness	
installation	flexible build (easily modified) robot injection point easy dismantling for robot recovery base station buried sections	

currently being realized. This will be used for the training, testing and commissioning of the robot system starting the end of this year.

7 References

[1] P. van Thienen, M. Maks, D. Yntema, J.-P. Janssens, B. Bergmans, R. Diemel, M. Helgers, P. Horst, E. Trietsch "Continuous robotic inspection of pipes for data rich asset management," *CCWI conferenc*e, Sheffield, 2017. https://doi.org/10.15131/shef.data.5363899.v1

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