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Towards autonomous sewer robots: the MAKRO project

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Abstract

We expose current research and development in information technology that deals with building and controlling autonomous service robots for performing inspection tasks in sewerage systems that are inaccessible for humans. The problem is explained, the physical and legal boundary conditions for operating sewer robots are described, the state of current sewer inspection technology is sketched, and the need for using advanced technology in this area motivated. Respective work that we have been doing for the last four years, and that is currently being pursued in the MAKRO project, is presented. The main technological and control problems are described, and how Artificial Intelligence research and technology may be employed to solve the latter.

1. Introduction: what's in a sewer

Most municipalities in the world run sewers. [2] They may differ in age, making, extension, and elaboration, but in any case they incorporate a large infrastructure investment – for many towns their largest item in capital goods overall. The standards of sewage treatment and, consequently, the sizes of sewers differ greatly in different countries, but their overall length is enormous, to say the least. Total sewer pipe length in Japan, e.g., was 250,000 km by the end of 1994 (Fukui, 1994). Communal sewers – not counting private ones – in Germany were about 400,000 km in length in 1997 (Dyk & Lohaus, 1998); and they are growing.

If designed, built, and used properly, a sewer may just work for a long time: Dyk and Lohaus (1998) report that 31.4% of the communal sewers in western Germany were 50 years and older. However, it is mandatory to put effort into sewer maintenance to guarantee proper function, to protect the large investment capital spent to build them, and to prevent damage from the sewer itself, from sewage treatment plants, and from the environment.

Maintenance has to begin with inspection. Larger pipes, i.e., those wider than 80 cm inner diameter, are considered accessible for humans and can be inspected by walking through. But only relatively few mains are accessible (11%, cf. Dyk & Lohaus, 1998), the vast majority of sewer pipes is not, diameters going down to 15–10 cm towards inlets from single houses. Typically, inaccessible sewers are inspected visually by humans operating a motor driven camera platform – a costly and slow procedure.

In the rest of this paper, we argue that building autonomous mobile robots for inspecting inaccessible sewers is feasible, makes sense economically, and necessarily involves *Artificial Intelligence* (AI) technology and research. The presented results are based on a joint feasibility study (Berns et al., 1996, 1997) and on technical work that we have been doing since 1995. We start with a sketch of the state of the art in sewer inspection, based on which we explain the potential of inspection using autonomous mobile robots. The main section describes the solution concepts that we have developed in the ongoing MAKRO project, and the current state of their implementation. After that, we point to existing work of other researchers which employ advanced information technology for automating sewer maintenance. We conclude by summing up the arguments.

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[2] We use the term *sewer* to unspecifically denote storm drains, sanitary sewers, and combined systems.

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2. State of the art in sewer inspection

A standard, state-of-the-art technology of inspecting inaccessible sewers is emerging now over different countries. This section gives a sketch of the recent inspection practice; Bölke (1996) describes it in all detail – at least its German version.

As a boundary condition for technology and research in sewer inspection, there are large differences in the procedural regulations concerning if, when, and how to inspect. In the US, e.g., there is, to the best of our knowledge, no regulation that would urge or force a community to regularly inspect their sewers. In Germany, on the other hand, there are states in which inspection of the complete sewers of all communities are mandatory every 10 years. The European norm EN 752-7 (CEN (European Committee for Standardization), 1998) includes general inspection requirements as well as ample reference to national regulations. In any case, we assume that many municipalities all over the world have developed or will develop a regular sewer inspection pattern – motivated by laws or by own insight.

State-of-the-art inspection of inaccessible sewers is *visual.* Fig. 1 shows the scheme: a human tele-operates a wheeled platform equipped with a colour, high-resolution video camera and a lighting system. The operator's duty is to detect, localize, classify and protocol all features in the pipe, such as laterals and damages. The inspection is documented by a video tape of the complete procedure, by a graphical and textual protocol of all findings, and by photos of particular damages, like the one in Fig 2. The protocol is sometimes requested in digital form suitable for input into sewer information systems.

The camera platform is tethered, the cable serving for energy supply, for transmission of control from the operator, for data transmission to the operator, for measuring the distance travelled, and for pulling in manually the platform in case of malfunction. Of obvious help, the cable is also a tremendous hindrance. While the platform drives along a pipe, the cable rubs along the pipe bottom. Depending on its weight and on the ruggedness of its surface and of the pipe, the friction increases with the distance travelled, effectively stopping the platform typically after 50–200 m. If bends are present, the range of operation shrinks again: cable friction is severely increased by bends, and the design of the platform frames, which is typically longish and rigid, makes turning along narrow bends physically impossible. The same is true for steps, which are frequent in sewers at places where laterals of smaller diameters join mains with larger diameters and their bottom level not meeting. It is currently considered unthinkable – or at least unheard-of – that an inspection platform climb into such a lateral.

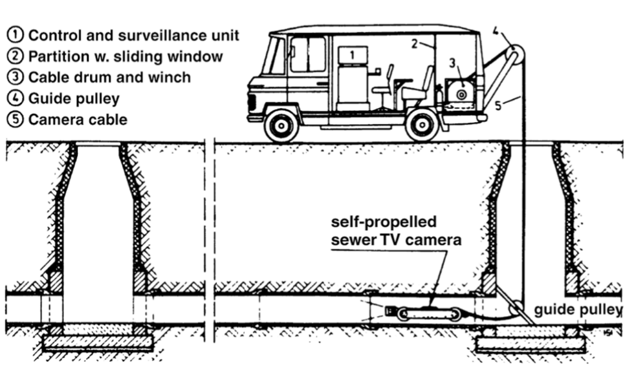

Fig. 1. Schema of current visual sewer inspection. From ATV (1991), adapted.

This hindrance by the cable has its price – in terms of handling trouble and, consequently, in terms of inspection cost. The camera platform has to be hauled in frequently. Moreover, the driving speed of the camera platform in the pipe is normally restricted to enforce inspection accuracy. Specifications of maximum speeds and average inspection speeds vary; 15 and 2 cm/s, respectively, are typical values (Bölke, 1996, p. 197).

In consequence of all that, an inspection team of operator and assistant using operating equipment (van, control post, cable handling mechanism, camera platform) for over $100,000 can inspect just a few hundred meters per work day, 600 m being an expected value. A typical price for an inspection only these days in Germany is around $5 per meter (Berns et al., 1996, Part III), which means that a complete inspection of the communal sewers in Germany would currently cost $1900 million. A severe cost overhead for cleaning and sewage by-passing of the sewer part that has to be inspected must be added. The price, by the way, is in the end paid by the users of the sewer, i.e., citizens and industry.

If the cable causes trouble, why not do without? Why not simply replace it by a radio link? Implementing the full functionality of the cable-tied vehicle on an unleashed one implies that there must be a different, but equally precise procedure to measure the travelled distance (odometry), that the vehicle must have its own energy supply (batteries), and that the radio link allows for the same quality and transmission speed of data, control commands, and video images as the cable.

But high-bandwidth wireless transmission through underground pipes suffers from high damping – so the video images do not arrive undisturbed. Precise odometry is difficult to achieve on a vehicle that has to drive in a slippery sewer – so positions of detected features cannot be localized precisely. Lighting up a sewer for good sight consumes much energy – so a battery-powered vehicle can impossibly work all the time with full lights on. These points, of course, are also true for an autonomous platform, so we will revisit them below.

Fig. 2. Image from a conventional sewer inspection. Tree roots grown in through a leaking joint. (Image by courtesy of RHENAG, Cologne)

The main inspection sensor is the camera. Some sewer features are obvious from the video image, such as laterals or drastic damages, some require considerable expertise to detect. Used pipes typically show some degree of corrosion and are covered with a film of dried mud and algae, hiding smaller cracks to direct sight. Particularly hard to see is damage under the streamlet of sewage, which is always present in a sewer (except storm drains during a drought). Another field for expertise and training is to assess from the video image the degree of pipe deterioration, given a damage. This is the chief task for the inspection operator, as it determines if and how urgently action must be taken: It makes a difference whether a crack is just on the surface, or goes through the pipe material, or if a crack web puts at risk the stability of the pipe.

3. Potential benefits of a new technology

A radical change in sewer inspection technology, based on using *autonomous mobile robots*, could enhance inspection quality, yet reduce cost. Moreover, it could open up a perspective to view differently the whole process of running and maintaining a sewer.

An autonomous mobile robot, as it is termed in Robotics and AI, is a self-steering vehicle. It is not tethered with a cable, and it is able to operate most of the time without being controlled by a human operator. Some obviously required features of such an autonomous robot are an on-board computer with suitable software that controls the vehicle, rechargable batteries of sufficient capacity to ensure a reasonable working time, various sensors to perceive its environment, and video equipment. A radio link to a human operator should be supplied whenever possible, in order to transmit data from the robot to the surveillance unit, and to allow for the operator to change the robot's mission profile or to take over control in unforeseen emergency cases.

In this section, we describe, first, the benefits of substituting current inspection technology by autonomous sewer robots, and, second, sketch the vision of keeping autonomous robots permanently in the sewer. These results are abstracted from the study by Berns et al. (1996).

3.1. Substituting current technology

The challenge for sewer inspection is to 'cut' the cable. If this were possible within the limits of a robust technology, then there would be a large potential for saving cost and for enhancing inspection quality.

The savings potential should be obvious from the previous description of handling current inspection platforms. For a more detailed analysis, consider the scenario that an autonomous inspection robot works in the sewer all day; the human operator can contact it by wireless transmission at selected shafts or manholes that it passes, transmitting inspection data to the operator and control information to the robot. The wireless connection can be established by putting an antenna into the manhole; being close to the robot, transmission rates can get arbitrarily high, at low energy consumption. As the robot continues inspecting, the operator team can prepare the next contact point and cross-check recently transmitted data.

Assuming a net inspection speed of 10 cm/s for 6 h per day on site, of which 1 h is spent sitting for data transmission, expected inspection distance per day is 1800 m, i.e., triple the distance usually achieved today, at comparable investment and operation cost.

As to inspection quality, there are recurring complaints about the state of the art – e.g., Bölke (1996), p. 2 – that it be inherently subjective, qualitative, and error-prone. Autonomous inspection robots would not magically *solve* the problem, but *require* to use a software based, maybe partly heuristic, but systematic procedure for automatic feature detection. We will come back to this point below. In any case, developing sewer robots for substituting current inspection technology would push the existing need for 'objective', standardized tools and procedures for detecting features in sewers.

Another quality issue comes together with the cost argument. As sewer inspection today is prohibitively expensive, many municipalities run their sewers not knowing what is really going on down there. For example, they would flush sewers regularly (in Germany about once a year, at current cost $\approx$ 4.60 DM/m), not knowing where that is required by actual sedimentation, and where the sewer is neat and clean by regular sewage flow. Moreover, municipalities have no practical chance to run sample inspections for checking whether the flushing job has been done well – be it by own staff or by contractors. It is suspected (Berns et al., 1996, Part III) that the sheer existence of cheaper inspection technology would raise the quality of maintenance work for sewers; in particular, more detailed knowledge about the sewer reality – which would come from more frequent inspection – would help reduce flushing to the occasions necessary.

The new technology could also be used in *private* sewers, which work the same way like public ones, but – at least in European countries – are currently subject to less rigid regulation. Probably not many house-owners wish to operate personal sewer robots, but there are huge private sewers, e.g., in the chemistry industry or the military, and some of these owners want to document high environmental standards. In all such cases where the sewer owner is also its user and has to pay for the maintenance, the cost argument is crucial, and it will become unavoidable one day when regulations for running private sewers get tighter.

3.2. The vision: life-long sewer robots

The strategy of replacing current inspection technology by autonomous robots seems promising as a first step both for exploring the field and for familiarizing involved staff with a new technology. The full potential of sewer robots, though, is exploited only in another, more visionary scenario: Robots permanently working in the sewer. To make this a reality, some organizational and technical problems must be solved.

To supply the sewer robots with energy and mission data, and to collect the data that they have recently acquired, docking stations must be installed (preferably in manholes). Energy for recharging the robot's batteries is to be transmitted contact-free by inductive coupling, and data as above by short-distance, low-energy, high-bandwidth wireless transmission. Existing sewer information systems must be changed so as to allow on-line access by robots.

On the technical side, robots that work, in principle, life-long in the sewer have to have certain physical, sensor, and control features. They must be able to follow bends and steps to not be engaged in a single straight sewer section. They must be able to withdraw to a suitable place (such as a manhole) and shut up in case of sudden raise in sewage level, e.g., at heavy rain. Their mechanics and motion control as well as their sensor configuration and interpretation must be able to cope with the sewer non-flushed. Their self-localization methods must be fool-proof. And – to mention the most obvious point last – there must be a rescue strategy and procedure in case a sewer robot breaks down in action.

Each and every of these points is a challenge in itself – not to mention their combination. It seems, though, as if they can be developed gradually from the previous scenario of replacing current technology, where new features can be added to the 'conservative' sewer robots if, when, and as far as they yield in terms of cost or quality. Berns et al. (1996) sketch a family of research projects over ten years, which in part depend on each other and could be steps towards realizing life-long sewer robots. To end this section, let us name their topics, showing both the research problems to be solved and some concrete application potential of sewer robotics: Each of these items would help make sewer maintenance cheaper or better in some respect, but are currently far beyond the feasible.

- Multi-segment, articulated sewer robot platform. This project, named MAKRO, started at the end of 1997. It will be described below.
- Sensor equipment and interpretation for detecting injection of certain illegal (poisonous, corroding) substances into sewers.
- On-site automatic characterization of the pipe state (geometry, corrosion, flow, condition of joints).
- Autonomous measuring of sewers and features in them.
- Sewer information system for providing robot access to all sewer-relevant data available, for managing the information provided by sewer robots, and for assisting humans in deciding about maintenance actions.
- Small team of (3–5) sewer robots and the required infrastructure for operating jointly in sewers for a limited amount of time.

4. The challenges of sewer robotics

4.1. Controlling autonomous sewer robots

Many robotics research projects use either simulated electronic environments or regularly structured laboratory environments. In both types of environments, it is usually easier to implement efficient solutions for robot control problems, because these artificial 'worlds' are often less complex – in terms of structural variance and dynamic changes – and better known than 'real world' environments, like sewers. A common approach to control a mobile robot is to equip it with an abstract description of the 'world' in which it shall operate. This description is called a *world* or *domain model*, and it usually contains all or most of the significant features of the domain that may be used by the control programmes.

There are three basic problems that make real world robot applications more difficult than those in artificial worlds – be it the application domain of sewers or any other class of robot application. In particular, they make it impossible to rely solely on classical control theory approaches to robot control, but require employing some AI technology.

First, the world is not completely known, i.e., no domain model is given in advance that includes all important and relevant domain features, so the robot must be prepared to adapt its world model when needed. This fact in sewers necessitates regular inspection in the first place. If everything of interest in a sewer were known, then there would be no reason to inspect. We assume that the robot will be equipped with a suitably encoded version of a sewer map, as it can be obtained from a sewer information system. The data in the latter one can be based on either sewer construction plans, or on actually performed measurements of the sewer. Anyway, we must take into account that this map data can be wrong: the actual construction of a sewer part may diverge from the plan, illegal or poorly constructed laterals may not be present in a map, and so on. Not all of the a priori unknown sewer features directly affect robot control: overlooking a leaking joint is an inspection fault, but does the robot no harm. Some features painfully matter for control, though. The robot *must* sense an encrustation to avoid getting stuck in the pipe. It *must* sense a lateral sticking out into the main to avoid damaging its sensors. It *must* sense a dislocation of the pipe bottom to avoid crashing down.

Second, the world is only partially observable, i.e., sensor data may be ambiguous or noisy and cannot be assumed to be correctly interpretable for deciding about and guiding action. Again, this is the case both for the very inspection part of sensing and for the sensing necessary to warrant the robot's integrity and orientation. (The sensor configurations that get used for these two observation tasks may overlap). These sensoric problems that exist even for lab robots are intensified for sewer robots by difficult and differing lighting conditions, dampness, and differences in pipe materials; drips and dirt may splash on and adhere to the sensors; and the whole system, including the sensors, must be sealed water-tight.

Third, actions can fail, i.e., they cannot be executed with guaranteed precision and success. Whoever walked a sewer knows it is impossible to position a robot precisely on the slippery ground. Stopping it does not mean it will stand still: it may drift towards the pipe bottom and along the pipe fall, pushed by the sewage current. The exact surface within the sewer is not known in advance: pipe profiles that used to be circular when built years ago may have changed by encrustation, wear-out or damage; the exact geometry is downright unknown at shaft bottoms and at joining laterals. In sum, motion (and inertia, for that matter) has to be controlled based on sensory feedback, which can safely be assumed to be unreliable.

A sewer has obviously much structure that can be exploited for sewer robot control. After all, the robot works in a pipe system; it must be prepared to encounter many, but not arbitrary world features; it has a limited set of tasks to do; no humans physically interfere. So we need not solve all the problems of AI first to be successful in sewer robotics. Getting first experiences with sewer robot control is even possible in lab pipe networks. For instance, we have used a dry, non-operational concrete sewer pipe network (Fig. 3) to that end; using small indoor PVC pipe networks is a cheap and handy alternative.

4.2. Constructing autonomous sewer robots

Though we view the control problems of autonomous sewer robots as the most challenging ones, they are not the only problems. Constructing autonomous robots is also a challenge to mechanical and electronic engineering.

The trouble starts with designing and building a suitable mechanics that is small, robust, water-proof, dirt-resistant, flexible, efficient, affordable, you name it. Required engineering efforts include developing new, smaller, and better sensors with automatic cleaning devices or dirt rejecting covers, lighter batteries with higher capacities, as well as robust, long-life drives and transmissions. The non-AI challenge continues with designing the appropriate controller, computer and sensor hardware, and operating systems. All these challenges have been adopted by a project consortium of four partners, which are currently implementing a sewer robot prototype in the frame of the MAKRO project.

4.3. The MAKRO project

In Section 3, we sketched a family of research projects as steps towards realizing fully autonomous sewer robots that may be employed for various application purposes. The first project of this family, MAKRO,

Fig. 3. The LAOKOON-net, a dry sewer net not in operation, constructed by RHENAG, at the GMD site in Sankt Augustin, Germany.

commenced in the last quarter of 1997. The goal of this project is the construction of a working prototype of an autonomous sewer robot platform. At the end of the project, this prototype shall be able to drive completely autonomously through a part of a real sewer in the town of Siegburg.

Project partners in MAKRO are rhenag (Rheinische Energie Aktiengesellschaft) central administration in Cologne, Inspector Systems Rainer Hitzel GmbH in Rödermark, Forschungszentrum Informatik (FZI) in Karlsruhe, and GMD – German National Research Center for Information Technology in Sankt Augustin. Competences and work areas are roughly distributed as follows. Rhenag, the MAKRO coordinator, supplies expertise in operating sewer systems, and organizes experiments in real sewers. FZI and Inspector Systems cooperatively design the mechanical parts of the robot, and Inspector Systems actually builds them. FZI also designs custom electronic parts and implements the internal sensors and some of the basic communication and operating software. GMD designs the external sensor equipment, which is then assembled by Inspector Systems. The main task of GMD is to design and implement the high level AI control programs, radio link facilities, power management, and CPU equipment.

Aimed at demonstrating the feasibility of autonomously driving sewer robots, this platform will not yet carry an application like automatic inspection or others that have been sketched in Section 3. To make the project success feasible, we require a roughly cleaned sewer and dry weather conditions. The sizes of pipes in which the robot shall be able to drive is limited to the range of diameters between 30 and 60 cm. More than 70% of the inaccessible German public sewers are within this size range.

In the next section, we will first sketch some of the engineering solutions that are being developed in the MAKRO project. Then we give some detail of problems that are unavoidable in sewer robot control. We also briefly state AI approaches to attacking these problems.

5. Design of the MAKRO robot

5.1. Mechanical design

For sewer robotics, the kinematics of the robot itself is a challenge. Remember that pipes to inspect may be very narrow. Remember further that sewer robots have to climb small steps and turn at bends. Consider components necessary for such a robot: motors, gears, axles; batteries; data buses, computer, storage, and controller hardware; a variety of sensors; data transmission components; and a housing around all that. Then chances are high that a rigid robot frame containing it all does not fit into the small pipes or is not maneuvrable enough to turn or climb.

An obvious solution is to make the frame flexible horizontally and vertically. An example design is sketched in Fig. 4, where the idea is to have rigid containers for the necessary components and couple them by movable joints of three *degrees of freedom* (DOF), namely pan, tilt, and rotate. Depending on the geometry (number of containers, container and wheel diameter, ground clearance, container length, turning angles of joints), a robot with such a kinematic design can obviously provide the required maneuvrability, space, and

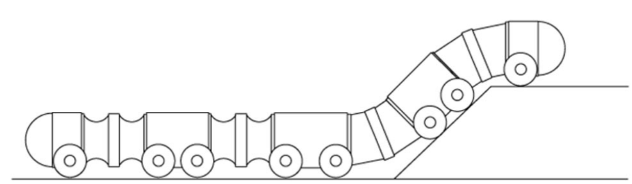

Fig. 4. Initial sketch of a five-segment, articulated sewer robot with active joints (image by courtesy of FZI).

small diameter. The two end segments shall contain duplicate sets of most of the *external sensors* (see below), which yield data from the environment. These data are a required basis for autonomous navigation. The symmetrical design allows the robot to navigate back and forth, e.g., if an obstacle in the sewer is encountered that cannot be overcome.

The above sketched initial design has been refined during the last years. Instead of four drives per middle segment, the first prototype (cf. Fig. 5) has only two drives – one propulsion on either side – per segment. This reduces weight, energy consumption, and control complexity, but does not severely reduce the traction. As a byproduct of this design decision, the middle segments could be made shorter, which resulted in a better kinematic flexibility. This is required for performing turning maneuvers at narrow pipe junctions. Each segment has a diameter of 16 cm. Segments and joints add to a total length of approximately 150 cm. We aim at keeping the total weight of the fully equipped robot below 30 kg.

5.2. Processor and communication architecture

The flexible design of MAKRO results in an enormous control complexity. Due to this, we have chosen a distributed processor design for the computing hardware. The robot's main control program runs on a PC104+ computer on-board. The PC104+ has a standard Pentium MMX 166 MHz CPU, a 2 GB hard disk, a framegrabber for acquiring camera images, a wireless ethernet card for exchanging data during our experiments, the usual serial/parallel interfaces and graphics chips, and a CAN bus interface card.

The latter provides the hardware for the robot's internal communication with seven SIEMENS C167 microcontrollers. The microcontrollers are smaller processors with a large number of interfaces for the sensors and other hardware devices. They locally control the steering of the propulsion and joint motors, preprocess the sensor readings, tag and route them to the main control program.

Central control on the PC104+ comprises mission control, route planning and navigation, motion control, and coordination of the microcontrollers. The operating system of choice is *Real Time Linux*, an extremely stable system that is especially well suited for running robot control programs.

5.3. Internal sensors

The MAKRO robot is equipped with a set of *internal sensors*, serving mainly for control of the robot's posture, i.e. the relative and absolute positions of the robot's segments and joints, and the robot's posture inside the sewer pipe. Odometry (see above) is based on counting impulses provided by *wheel encoders*. For each joint, there are three specially developed sensors which yield the current absolute angular values of the joint's

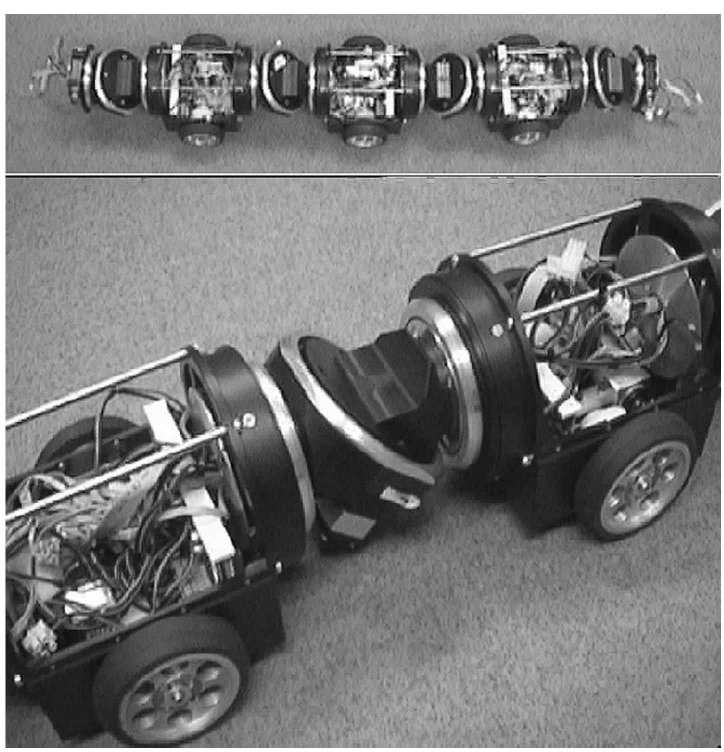

Fig. 5. Three middle segments of the five-segment, articulated sewer robot MAKRO (up), and close-up of an active joint (image by courtesy of FZI).

pan, tilt and rotate positions with a precision of 0.25°. These data are most important when the robot performs a turning maneuver.

Each container segment includes a two dimensional *inclinometer*. This sensor type supplies data – two angle values – on the absolute position of a segment in space. If the robot – due to wheel slippage – leaves the bottom of a pipe while trying to drive straight, it goes slowly up the pipe walls. The inclinometer can detect the resulting tilt, and a control program can correct the motion.

The fourth internal sensor type – developed by our partners FZI – yields data which indicate whether a wheel touches the ground or not. Based on foil pressure sensors, these sensors measure the pressure that is being exerted on them by the weight of the robot. This data is needed in various control situations. For example, signalling that a particular wheel lost contact to the pipe indicates that the wheel encoder data of this wheel, while being detached from the pipe surface, are useless.

5.4. External sensors

The robot's external sensors enable perception of its environment. Obstacle detection, collision avoidance, motion control, and *landmark detection* – a subtask of self-localization – subroutines rely on the external sensors. Most, but not all of these sensors are built into the two end segments. Each middle segment contains only a number of simple infrared range sensors, required for controlling turning maneuvers. This sensor type can measure approximate distances in a range between 10 and 80 cm up to 14 times per second.

The end segments contain four ranging sensors, a stereo camera head, two laser projectors, and a lamp. The arrangement of these components is sketched in Fig 6 and shown in Fig. 7.

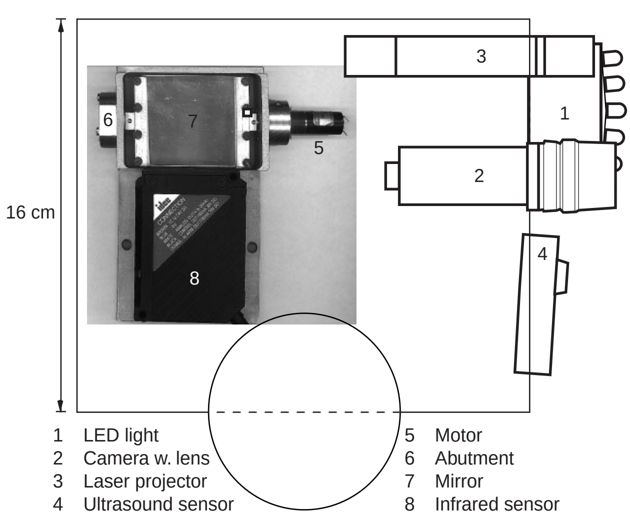

Fig. 6. Arrangement of external sensor equipment in the end segments of the MAKRO robot, sideview.

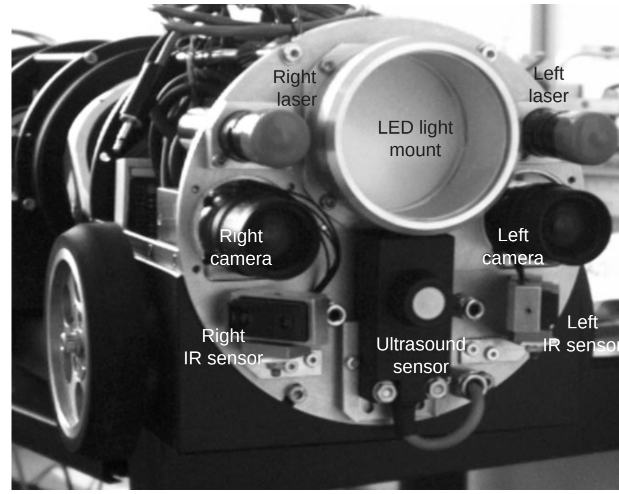

Fig. 7. Frontview of an end segment of the MAKRO robot. Protective glass covers are removed.

To light up the dark sewer for taking images with the cameras, the robot is equipped with a specially developed lamp. It consists of 22 ultra bright white LEDs, arranged in a circular symmetric fashion. These LEDs have an excellent efficiency. Consuming only 1.6 W, they are bright enough to light up sewer pipes of the sizes under consideration, 30–60 cm, for the two sensitive cameras (0.1 lux). No diffusor is needed. With a radiation angle of 70°, the light is already well diffused in a distance of only a few centimeters from the lighting device.

In Fig. 7, the central rectangular black unit is an ultrasound range sensor, capable of measuring approximate distances in a range between 20 and 80 cm. It is slightly tilted so that it points to the pipe ground. The main purpose of this sensor is the detection of obstacles that block the pipe.

The smaller rectangular units to the left and right of the ultrasound sensor (Fig. 7) are infrared ranging sensors of the same type that is built into the middle segments. Tilted towards the pipe walls, these sensors shall detect laterals. If a lateral is detected with the aid of one of these sensors, and if the robot's mission plan prescribes a turning maneuver at this joint, then the robot stops, turns on the LED lamp, takes two images of the joint with either camera, and turns off the lamp. The images serve as basis for a *three dimensional reconstruction* of the pipe joint, yielding coordinates of parts of the surrounding and joining cylindrical pipes with respect to a coordinate origin on the robot.

The schema of the stereo camera setup, the *stereo rig*, is depicted in Fig. 8. The cameras' optical axes cross in approximately 1 m distance. The *stereo basis*, i.e. the distance between the optical centers of either camera, is 12 cm. Image overlaps are shown as white triangle resp. as triangle formed by white triangle plus dark trapez area. Base widths of white triangle and dark trapez are

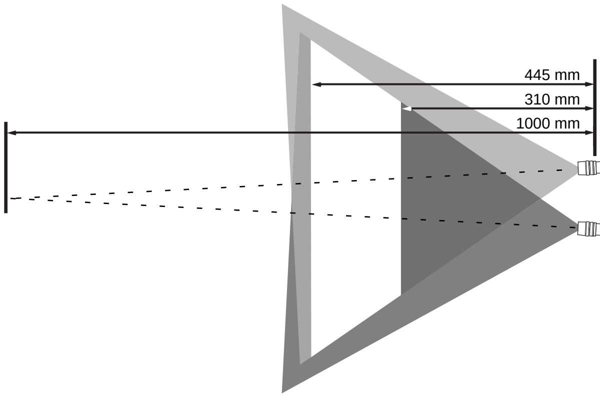

Fig. 8. MAKRO stereo rig top view.

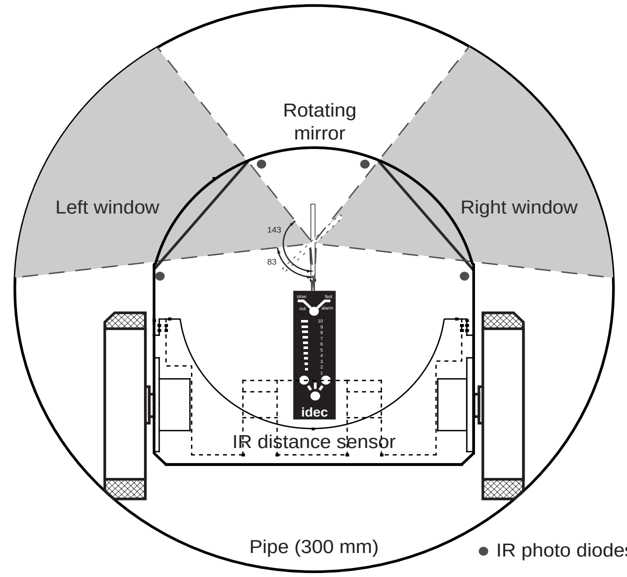

Fig. 9. Infrared range scanner measuring scheme.

slightly greater than standard pipe diameters of 30 cm resp. 50 cm. This means that from a distance of 310 mm resp. 445 mm from the camera centers both left and right pipe walls are visible in the overlapping image regions of the left and the right camera, a prerequisite for dense 3D reconstruction.

The achievable precision (better than 1.3 cm) of the reconstruction method is expected to be sufficient for the intended purpose, namely to use these data to plan the motions of the robot's segments and joints for turning into the lateral. As side effects, we expect that this method allows for detecting deformations of the pipe profile and for determining the angles between laterals and mains where possible.

The large leftmost unit (shown as photo in Fig. 6) is a specially developed range scanner, based on an IDEC infrared range scanner that includes a *Position Sensitive Device* (PSD). Capable of performing up to 150 measurements per second, the sensor emits infrared beams which are reflected by a mirror that rotates with a constant velocity. Some of the emitted beams penetrate windows on the upper left and right side of the robot (Fig. 9), while the others are reflected inside the robot. The latter ones are being filtered out.

The scanner is exploited in two situations. First, it scans the pipe walls while the robot drives through a pipe. The measurements are dense enough to detect every inlet that the robot passes. This contributes to self-localization. Second, the scanner may measure the distances of the end segment while it is entering the opening of a lateral during a turning maneuver. This may help avoiding the robot's colliding with a pipe wall.

Finally, the laser projectors can be used for projecting extremely bright and sharp regular light patterns (*structured light*). They can be used by special image processing routines which are currently in an experimental stage. At the same time, only one laser and the opposite camera are being used. Projected into a cylindrical pipe and 'seen' through the opposite camera, the cross laser pattern shows regular distortions. These depend on the relative orientation between camera and laser projector, and the posture of the front segment with respect to the sewer pipe axis. The former is known, and the latter one is to be computed.

It should be mentioned that all optical equipment, i.e. lenses, IR sensors, and lights, is protected by glass with a dirt and moisture rejecting mineral cover. Though not being an ideal, long term solution, the covered glass performs much better than uncovered glass.

6. Sewer robot control approaches

6.1. Motion control

To control motion sensibly – ultimately, to apply the right voltage to the right motor at the right time – a robot needs a kinematic model of itself in its current environment, how detailed or crude, how explicit or implicit that model may be. If the robot in question is a manipulator arm, say, in a car factory, the model is normally programmed or taught-in, and the robot kinematics (motor precision, stiffness) as well as the environment are designed such that the model fits. That does not work for sewer robots. Let us give some detail about two independent, but related points: motion imprecision and sewer robot kinematics. We have found learning techniques helpful for attacking both problems, and we here point at the respective learning approaches used in our own sewer robotics studies.

6.1.1. Motion imprecision

The sewer has to be accepted as the environment of a sewer robot as is, with all its slip and sludge. Two motor commands that are identical in terms of forces and timing are likely to produce different motions at different places. In addition, robots in pipes are in permanent danger of toppling over, so permanent tilt control is mandatory.

As an example, consider KURT (Kirchner & Hertzberg, 1997), a six-wheeled, shoe box sized sewer robot test platform built to study sewer robotics problems in a dry sewer – the LAOKOON-net (Fig. 3). Owing to its flexible wheel control, KURT is able to turn on the spot on flat terrain. Turning in a manhole in a sewer for entering a lateral, however, is more intricate. Due to the pipe geometry, the bottom of a manhole is dented. Turning in this dent, KURT does not always touch the ground with all its wheels. Only the front and back wheels would have permanent contact during a turn. Occasionally, the middle wheels also touch ground, causing unpredictably varying traction and making useless every practical model of rotational forces and timings.

In our study, we have solved this problem in the following way. The current junction is first classified as an X-, T-, or L-shaped junction, using data of an ultrasound scan. (The result of this classification is also used for determining the current location by mission control – see below.) For each of these classes, a sequence of subgoals was defined manually for each turning maneuver (right, straight, left), respecting the junction class geometry and KURT's sensor configuration. For example, turning right in an X-junction means to advance into the manhole until the open pipe is straight to the right; then turn right until the pipe is seen by the front-right sensor; then keep turning until it is seen by the front sensor; then check whether the junction can be correctly classified in KURT's new orientation; and then enter the pipe. While turning, the ridges at the bottom of the manhole are used as additional help for localization. The motion during each of the turning phases is best described as setting-back-and-forth-while-turning.

When entering a large joining pipe from a manhole, KURT may initially be in a tilted position. The tilt control subroutines have proven to be able to correct the tilt very fast and reliably (Kirchner & Hertzberg, 1997).

6.1.2. Sewer robot kinematics

The articulated design of the MAKRO robot comes at a cost. The robot has a total of 22 DOF: 5×2 for propulsion, plus 4×3 for the three motors per *active* joint. For steering the robot, each DOF has to be assigned a suitable value. This can be either an angle – for the possible motions of an active joint – or a motor speed – be it a numerical setting, say, between 1 and 20 or a voltage. Each type of maneuver requires special, characteristic combinations of these values. Driving through a straight tube at a given speed would mean, for instance, that all joints are straight, i.e. the values for pan, tilt and rotation may then all be, say, 0°, and the speed for all 10 motors is the same, say, 5 cm/s. If the robot, while driving straight, leaves the bottom of the pipe due to wheel slippage on only one side, then it is endangered to turn over. Hence its motion has to be adjusted, e.g. by reducing the speed of the motors on the other side. From this example it is clear that controlling the robot means to find a suitable combination of the DOF values that is appropriate for the current situation.

But the space of possible combinations is immensely large: for an angular resolution of 0.25° for each joint DOF and only 20 different speeds, it would be $1440^{12} \times 20^{10}$. It is practically impossible to formulate a kinematic model for a 22 DOF machine, i.e. a mathematical description of all possible control situations – limited only by the imagination of the programmer. Having such a model and the sensor data that describe the situation at hand, the required appropriate value combinations could be computed straightforward.

Worse, if this model should be worth anything, then all mechanic parts would have to be so precise and stiff that they would probably weigh and/or cost too much for a practical sewer robot. Finally, whenever the robot slips, tilts, or twists on uneven and slippery pipe surface, forget any precise analytic model whatsoever. The available sensors are not good enough to yield data of high certainty which can precisely describe the effect of the unforeseen slip motion on the posture of the robot. Other sewer robot designs than the one in Fig. 5 are possible, of course; the required maneuvrability together with the space constraints, however, necessitates a great number of DOF in any design.

Our studies suggest that a special *machine learning* – a subfield of AI – method allows the problem to be tackled. Kirchner (1997) uses a closed-loop, hierarchical version of *Q-Learning* to control a 16 DOF, six-legged walking machine. The motion pattern to be learned in this case was stable walking towards a target, but the experiments seem to indicate that the learning results can also be applied to multi-DOF sewer robot motion coordination. The general idea is to start with the definition of basic motion routines. The complex overall motion is then hierarchically assembled from these basic routines. In the walking machine, for instance, such basic routines are those which implement the swing and stance motions of individual legs. The complex walking motion is then assembled from suitable sequences of swing and stance motions of all six legs. The hierarchical organization of the original, complex motion allows the original learning space to be reduced to a set of relatively handy sub-spaces – the original space is enormous, consisting of all possible time sequences of motor commands along the multitude of DOF. As one of the research tasks in MAKRO, we investigate the application of this approach to motion control of the multi-DOF MAKRO robot.

6.2. Mission control

On a higher level, mission planning and plan execution monitoring are relevant AI techniques for sewer robotics. Given an initial position and a goal position on a digitized sewer map, the first task is to find a suitable path between these locations. This can be achieved by using the well-established method of *graph search* in the map. Often, a desired path is even explicitly given, namely, the inspection route. If there is a mission control challenge in sewer robotics, it is not in path planning.

Physical navigation along a given path can be more demanding. We assume it is not economic to plaster sewers with beacons and keep these *artificial landmarks* clean and readable. As a fact, signals of the Global Positioning System (GPS) are inaccessible in sewers. In consequence, a sewer robot has to rely on on-board equipment to determine its position with respect to the map. No general statement is possible about how difficult this is in practice. Simple odometry is not reliable in a slippery sewer pipe. However, given an ideal map (which is correct, complete, and states the joining angles of laterals) and given a method to measure reliably turning angles of the robot (such as by using gyrometers or summing over the internal tilt angles in a multi-segment design as in Fig. 5), then navigation according to existing landmarks, such as manholes or joining laterals, is straightforward.

Now consider as an example the current sewer mapping situation in German municipalities. Traditionally, the only information available is a construction drawing of considerable age, typically coming on large rolls of paper, with drawings of more recent additions, coming on more large rolls of paper. Existing construction features are not sure to be in the plans: sometimes features are changed yet not reported in the construction process, and illicit additions occur. As mentioned earlier, a number of cities have started to build up sewer information systems, which include digitized maps. The map information is provided by preparing the old drawings manually or by feeding in available information from recent state-of-the-art inspection protocols. In any case, currently existing sewer maps cannot in general be assumed to be correct and complete. Add to that possible inaccuracies in motion control (see above) and feature detection (see below), and there lurks a navigation problem.

Our studies in sewer robotics include work on navigation of KURT in the LAOKOON-net (Hertzberg & Kirchner, 1996). The basic idea is to employ a probability based scheme for controlling the mission that takes into account possible action and feature classification uncertainty, a method that also has been successfully applied to office navigation robots (Simmons & Koenig, 1995). However, we have not yet attempted to correct the sewer map in this line of work, but allowed for relatively probable turning errors – due to KURT's one segment design and lack of adequate sensors – and landmark classification errors. With the multi-segment MAKRO robot, turning is only possible through actively bending joints between segments by pre-computed angles. If a turning maneuver (Fig. 10) succeeds, then we know exactly the direction into which MAKRO turned. Thus eliminating one source of uncertainty, there is now a chance to handle map flaws.

The visionary, long-term sewer robotics scenario would include many more mission control tasks that require AI technology. The first set consists of off-line mission planning tasks. Consider the idea of generating inspection plans or flushing plans for the immediate future automatically from all available sewer data, such

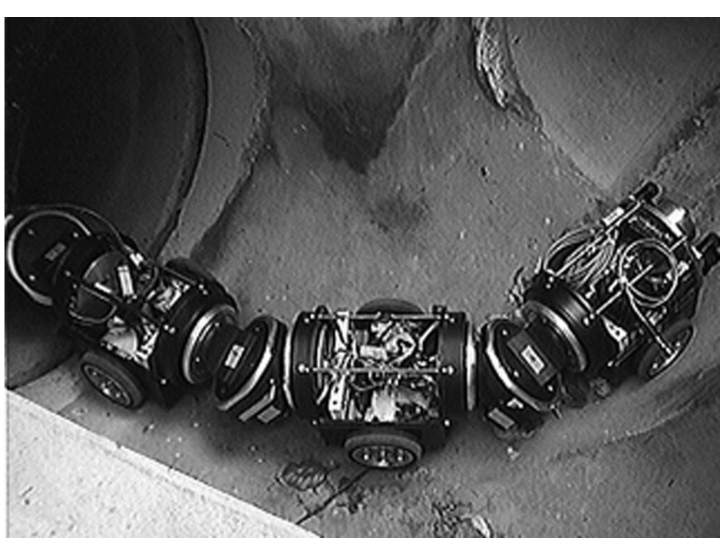

Fig. 10. MAKRO robot while turning in a T-joint of sewer test net.

as time of construction, materials, topology, and results of past inspections: an obvious application field for *knowledge-based systems*.

6.3. Feature detection

Finally, there is the problem of correctly interpreting sensor data of the sewer, or sewer *perception,* in AI terms. This subject spans a wide range of applications and problems, already sketched above: navigating, detecting damages, analyzing chemical substances, characterizing pipe state, identifying other robots, and measuring sewers.

6.4. General constraints on sensors for sewer robots

A number of constraints apply to the types and numbers of sensors that may be selected for the above tasks. The cylindrical sewer pipes with their mostly small diameter and the intended kinematic capabilities constrained the geometry of the MAKRO robot to an elongated, articulated design. As already mentioned, most of the sensors for perceiving the environment are placed in the two ends of the robot's housing. A fully autonomous sewer robot, with its battery of limited capacity and its narrow housing, thus can be equipped only with a rather small number of sensors, compared to a large office floor robot.

The sensors should be minimized in weight, size, energy consumption, and computing power needed to process their data. For instance, although they yield very precise range data, we did not choose current off-the-shelf laser scanners, because they are too large and too heavy to be mounted on the MAKRO robot. There would have been little or no space left for other sensors, and it would have made the end segments of the robot too heavy to be lifted.

A camera can only be used if the sewer is lit up. Lighting devices, like the ones that are mounted on current sewer inspection vehicles, consume much more power than, e.g., an ultrasound sensor, and thus reduce the possible maximum range of the robot and its operation time, if used extensively. Depending on the algorithms used, continuous video image processing may also consume a considerable amount of computing power, which might be needed for other purposes, e.g., the complex motion control.

However, video cameras are the type of sensor which sewer inspection operators are used to, and which yield very rich data, compared to other sensor types. It makes sense to use this wealth of data for specific tasks, which can hardly be solved using data of other sensors, like simple ranging devices. The method of three-dimensional reconstruction of pipe joints (see above) is one example for this.

6.4.1. Sensors for navigation

Cameras with a high light sensitivity are now available, allowing to reduce drastically the energy needs for lighting purposes as long as only landmark identification is concerned (damage detection might require different resolution and lighting). Moreover, if vision is limited to processing still video images, then the power consumption for lighting gets uncritical, and so does computing time consumption. In consequence, navigation can rely on image analysis as a source of information. More intricate cases can also be handled: For instance, if ranging sensors detect an obstacle in a pipe, then vision may be needed to determine whether this obstacle can be crossed safely.

Above, landmark classification in KURT has already been reported as determining the branch type (X,T, or L) of the joints in a manhole. This shows that unexpensive sensing techniques can also successfully be used for sewer navigation. In fact, KURT uses only inclinometers and ultrasound sensors for this task. Ultrasound is reflected very well by the concrete pipes of our dry sewer test net. However, these sensors may fail in a real sewer as dirt covers and different pipe materials reflect ultrasound differently and thus may yield unreliable data in some cases. Also, ultrasound sensors come in sizes that are too large to allow for mounting many of them in MAKRO's end segments. The closed design of ultrasound sensors prohibits customization. For these reasons, we decided to include only one of these sensors per end segment.

The initial configuration of external sensors for MAKRO has already been described. It relies heavily on infrared sensors with position sensitive devices, claimed to be independent of the brightness of the reflected infrared light beams. Respective experiments in real sewers with their different light reflecting and absorbing properties of different pipe materials and stains will have to unveil the practical reliability of these sensors.

Under the difficult sensor conditions in a sewer, more than one environment sensor type should be used at any time, i.e., the unescapable uncertainty should be countered by redundancy. Moreover, we expect that the AI technique of evaluation of correlated data from different sensor types, termed *sensor fusion*, is crucially needed.

6.4.2. Sensors for automatic generation of sewer state descriptions

Of course, navigation is only a means towards an end, namely, detection of faulty sewer conditions, which requires damage detection, sewer measurement, and sewage analysis. On the engineering side, for all of these applications either new sensor types have to be developed (damage detection, sewage analysis), or known sensor types have to be modified in order to make them suitable for use in an autonomous robot (sewer measurement, sewage analysis).

The complexity of sensor data processing for the applications varies. While a simple diagnosis system might suffice to process the data of a few electrochemical sensors for sewage analysis, damage detection and sewer measurement may be arbitrarily complicated. If vision is employed for extracting exact metrical information from images, then automatic offline camera calibration (Faugeras, 1993) is a challenging problem that has to be solved. Other than that, the methods and techniques for processing the sensor data depend on the technical sensors, which are yet to be developed – so nothing concrete can be said here.

7. Existing work in sewer robotics

MAKRO is not the only project that aims at improving sewer inspection and maintenance technologies. As another relevant line of research involving advanced information technology, there is work towards creating more ‘intelligent’ sewer inspection vehicles. Completed projects include KARO (Kuntze, Schmidt, Haffner & Loh, 1995) and PIRAT (Campbell & Rogers (1995)). Both projects were aimed at producing ‘smart’ vehicles – equipped with several different sensor devices – which are connected to a mobile control and surveillance unit by a cable. The research focus of both projects was developing methods for the automatic interpretation of sensor data to discover pipe damages mechanically and thus help automatize sewer inspection.

KARO, an inspection platform with exchangable sensor modules, employed *fuzzy logics* to fuse and interpret data from different types of sensors. In the PIRAT project, an *expert system* classified pipe damages in video images. The damages still had to be discovered by a human operator, and the regions in the images that showed the damages had to be marked manually. In both systems, the main control routines were not running on on-board hardware, but on a computer in the mobile control unit. The KARO platform has been described by its creators as a still experimental prototype, whereas the makers of PIRAT report to have employed their system for inspecting 5 km of sewers in Melbourne, Australia.

Some other projects related to sewer inspection are underway. Eiswirth, Hötzl, Kramp, Lazar and Merkler, (1995) describe preliminary work for a project going into the KARO and PIRAT direction. Clarke (1995) uses optical triangulation for measuring sewer pipe profiles automatically, aiming at a detection of noticeable pipe profile deformations.

The only work of which we are aware that deals explicitly with designing autonomous sewer robots in the sense of this paper is the one in the succession of the above-mentioned feasibility study LAOKOON (Berns et al., 1996) and in the MAKRO project. In particular, Kirchner and Hertzberg (1997) describe the sewer robot test platform KURT; Hertzberg and Kirchner (1996) give details about KURT’s navigation under uncertainty; Cordes, Berns, Eberl, Ilg and Suna, (1997) report the concept of the multi-segment sewer robot platform; and Kirchner (1997) presents results about learning motion coordination.

8. Conclusion

Let us conclude the paper by summing up the line of argumentation. Sewers are an important and expensive part of communal infrastructure. Maintaining them requires considerable effort; in some countries, this effort is even required by law. The current technology for inspecting inaccessible sewer pipes causes relatively high cost, which is in the end paid by the citizens and industry of the communities. Running autonomous sewer robots for the task promises to reduce the inspection cost to about a third of the cost for the conventional procedure. AI technology is crucially needed for controlling a sewer robot, as sewer robotics involves a particular combination of the imprecision, lack of knowledge, and resource constraints that are typical for so many real world service robot applications.

On the other hand, the problem is such that using current AI technology promises to yield usable results in reasonable time. A machine learning technique, hierarchical Q-learning, has proven to be a suitable tool for handling complex motions of robots with multiple DOF. Methods for planning routes based on complete maps of artificial environments, like sewers, are established AI techniques that can be used right away. Probabilistic navigation algorithms, like navigation under uncertainty, help overcome the flaws of odometry and false sensor readings. Computer vision methods can be used in a variety of ways. They yield rich data for navigation and motion control. But more AI-based methods, like updating and correcting maps or vision-based techniques for automating parts of the inspection process, are yet to be developed or adapted to the problems at hand.

The development of the MAKRO robot is well under way. A first prototype with a unique combination of current technologies as well as specially developed engineering solutions has been constructed. First control experiments in plastic pipes and GMD’s dry LAOKOON sewer test net started end of July 1999. If MAKRO succeeds, then the next research step will be to explore one of the possible applications that have been sketched in our long-range vision of sewer robotics projects. Whether a working sewer robot application is attractive enough to find a construction company that turns it into a product and markets it is still an open question.

The final frontier is social: convince the sewer maintenance people (and their standardization committees) to let a robot work on its own and believe what it finds. The point is: not AI alone is needed to make sewer robots practical – but it will not work without.

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