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# A Custom IR Scanner for Landmark Detection with the Autonomous Sewer Robot MAKRO

**Erich Rome, Hartmut Surmann, Hermann Streich, Ulrich Licht, and Karl-Ludwig Paap**

GMD – National Research Center for Information Technology
Institute for Autonomous intelligent Systems
<firstname>.<lastname>@gmd.de, http://ais.gmd.de/projects/Makro/makro.html

**Abstract.** MAKRO is an autonomous sewer robot designed for navigating in sewer pipes. In order to find its way to a specified goal manhole, it has to solve the self-localization problem. The sewer environment contains only few features that are usable as landmarks for re-localization, namely inlets, pipe joints and branching pipes. This paper describes how a custom 2D scanner involving infrared distance sensors with high sampling rates can be employed for robust and fast detection of inlets. Up to 150 measurements per second are preprocessed on a microcontroller, detection results are passed to higher level control programs on a faster CPU. The system requires only a brief initial automatic calibration. It is smaller and cheaper than comparable sensors, it is fast and it requires less on-board resources in terms of computing time, energy, and space.

## 1 The Autonomous Sewer Robot MAKRO

MAKRO is a prototype of an autonomous mobile robot platform designed for navigating in inaccessible sewer pipes. It is able to drive autonomously in sewer pipes of diameters between 300 and 600 mm, steered by navigation and motion control routines running on a PC/104 CPU, relying only on sewer maps and on data from numerous on-board sensors.

Such a platform can carry various applications for sewer maintenance, like devices for measuring the physical dimensions of sewers, sensors for detecting chemical sewage pollution, and more. This could help to make sewer maintenance faster, better, and cheaper, enabling communities to inspect or measure their sewer systems (cf. Encyclopedia Britannica (2001)) more often, as will be prescribed by forthcoming European legislation. A rationale for autonomous sewer robots is described in (Rome et al., 1999).

MAKRO differs from conventional inspection equipment in main aspects: A conventional inspection “robot” is tied to a cable that connects it to a surveillance unit. The cable provides supply energy, teleoperation control signals, and video signals, but it also limits the operation range. MAKRO, on the other hand, is unleashed and carries all the resources it needs on-board. MAKRO is an articulate robot consisting of six segments, connected with five active joints (cf. fig. 1(a)). Each joint is driven by three motors, enabling MAKRO to bend and lift parts of its 50 kilogram body for climbing and turning maneuvres. The six driven wheel axes and the fifteen joint motors add up to a total of 21 degrees of freedom for MAKRO 1.1 that have to be controlled. Conventional inspection equipment has only one large rigid body segment that prevents turning and climbing maneuvres.

MAKRO also incorporates a number of internal sensors. A thermometer for measuring the CPU temperature, pulse counters for odometry, optical sensors for reading joint angle encodings, and more. Sensors for data acquisition from the environment are mainly located in both identically equipped head segments. Each of them contains a stereo camera pair, lighting equipment, an ultrasound transducer for obstacle detection, four fixed infrared distance transducers, and the custom IR scanner which this article is about.

The MAKRO prototype is designed to operate in roughly cleaned sewers at dry weather conditions. Its housing is waterproof, and modestly resistant to corrosive substances. Some optical sensors are protected with specially coated glass that rejects dirt and water (cf. (Kepplin et al., 1999; Scholl et al., 1999) for more details on the robot construction).

MAKRO’s kinematics enables it to perform turns at sewer pipe junctions and to climb steps up to a height of 35 cm. These new capabilities allow for more flexible maneuvres and longer missions, since the robot does not have to be manually put into a branching pipe or into a pipe section behind a step. Figure 1(b) shows MAKRO 1.0 performing a turn in a dry test sewer. Basically, the duration of MAKRO’s missions is only limited by the on-board battery capacity. During our experiments, we achieved operation times of up to two hours with one battery charge.

(a) Sewer robot prototype MAKRO 1.1.

(b) Sewer robot prototype MAKRO 1.0 performing a turn in a dry sewer.

Fig. 1. MAKRO robot prototypes.

A typical mission of an autonomous sewer robot consists of putting it via a manhole $M_1$ into a sewer pipe, then let the system autonomously follow a prescribed route to a specified goal manhole $M_n$, and retrieving it from there. The robot is equipped with a map of the sewer system and it knows the start and goal manholes, and the route—or "path"—between them. It drives through the chain of pipe sections that the path consists of, passing more manholes and other landmarks, like pipe joints and inlets from houses. These three types of artifacts are basically all the landmarks that may serve for orientation and self-localization in a sewer. Self-localization is a capability required for controlling the correct execution of the navigation plan, i.e. controlling that the robot is always on the specified path.

Currently, MAKRO accomplishes only manhole and inlet detection. A vision-based method for pipe joint detection has also been tested (Kolesnik and Baratoff, 2000). In this paper, we will concentrate on robust inlet detection. This task could, in theory, also be solved by using 2D Laser scanners. Unfortunately, the currently available models, like those of Sick (2001), Schmersal (2001), and Leuze (2001) are too heavy (2.2–4.5 kg) and voluminous to be integrated into the MAKRO platform with its case diameter of only 16 cm. So we had to find a custom solution.

We argue that a cheap custom 2D range scanner based on an IR distance sensor with high sampling rate is an appropriate and robust solution for the task and superior to alternative methods, given the constraints and requirements of a sewer robot.

The paper is organized as follows. First, we briefly describe the sewer and summarize the state of the art in sewer landmark detection. We continue with a description of the custom scanner construction and the respective design considerations. The next section contains a brief description of the calibration and data evaluation procedures, and an analysis of experimental results. We conclude by summing up the arguments.

## 2 On Sewer Landmark Detection

### 2.1 Sewer Landmarks and Sewer Maps

Sewers consist mainly of smooth, uniform cylindrical or elliptical pipes. For purposes of navigating in a sewer, a robot needs distinctive local features that may serve as landmarks. Constructive elements like inlets from houses, manholes, and pipe joints (fig. 2) are well suited for this purpose. Position coordinates of inlets and manholes are recorded in sewer information systems. These data can easily be retrieved and converted into a map for robot navigation. Such a map is made up of descriptors for manholes and inlets, distances between these landmarks, information on pipe diameters and pipe materials, and more.

The information in sewer information systems can be erroneous, e.g. metrical information may be incorrect because recorded positions of manholes vary from actual positions. This can happen when the information is taken from blueprints and when the actual construction differs from the blueprint due to unexpected local requirements. Usually,

Fig. 2. Images of an inlet, pipe joints, and a manhole taken with MAKRO's cameras.

the blueprints are not updated in such cases. Also, there may be illegal inlets which are not recorded in a sewer information system. This means that map information is uncertain to some degree, and that an autonomous robot has to cope with this type of uncertainty. Navigation under uncertainty is ongoing research (Gasós and Saffiotti (1999); Moon et al. (1999)) and beyond the scope of this article.

### 2.2 State of the Art in Sewer Landmark Detection

The detection of sewer landmarks for self-localization purposes has already been approached using different methods. First navigation experiments with sewer robot test platforms have been conducted in a dry sewer test net at the GMD site in Sankt Augustin (Hertzberg and Kirchner, 1996). Figure 3 shows the net and a graphical map of it. The method for navigation under uncertainty of sensor information described in (Hertzberg and Kirchner, 1996) employed only a topological map of the test net, consisting of a graph and manhole shape information (L-, T-, X-shaped). The presence of a manhole could be detected by ultrasound sensor data evaluation. The manhole was then scanned by a different, pivoted ultrasound transducer. The manhole shape could be classified from the scan data by a specially trained artificial neural network. Although it has a high rate of correct classifications (75 out of 81 samples), this method lacks the capability of identifying individual manholes.

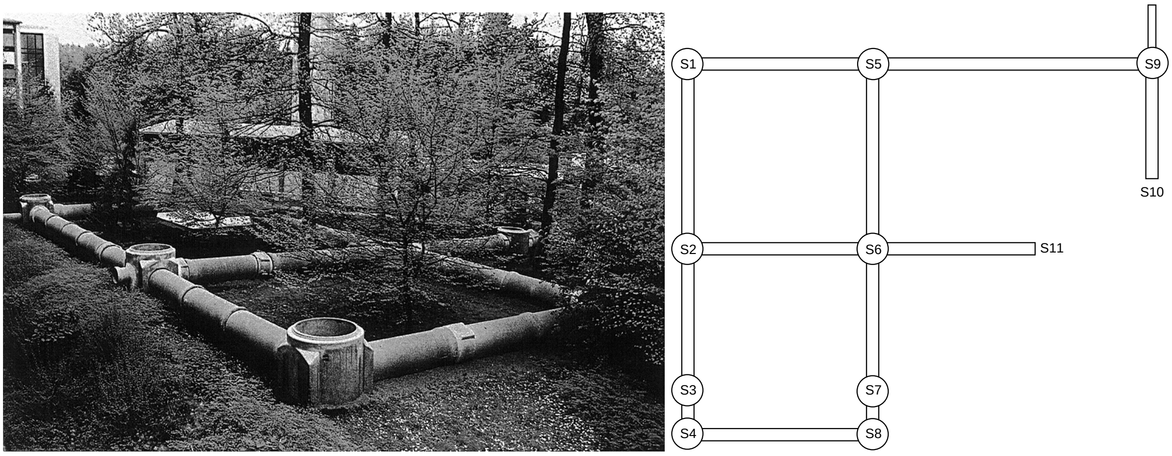


Fig. 3. Dry sewer test net, corresponding map.

For a more fine-grained localization, the method has been further enhanced by inlet detection using a second pivoted ultrasound transducer Schönherr et al. (1999) that permanently scans the walls of upper half pipe sections. This procedure is time consuming and requires a speed maximum that lies clearly below the recommended sewer inspection speed maximum of 20 cm/s.

Paletta et al. (1999) describe experiments with a method for discovering inlets in grayscale images taken with an onboard CCD camera. The method involves a time consuming training phase, whereas detection of trained inlets is rather fast. In real sewers, the robot would need to explore unknown sewer sections in order to perform the mandatory training phase. This procedure is not desirable in practice.

Campbell et al. (1995) and Clarke (1995), use different pipe profiling methods for 3D reconstruction of sewer pipes in order to automatically detect damages. The sensor devices are mounted on teleoperated sewer robot equipment, and the data evaluation is performed by a stationary computer in a surveillance vehicle. In principle, these profiling methods are also suited for inlet detection. But the required hardware equipment of Campbell's (1995) PIRAT system and Clarke's (1995) profiling instrument are too large and heavy to be integrated into the case of a small autonomous mobile robot.

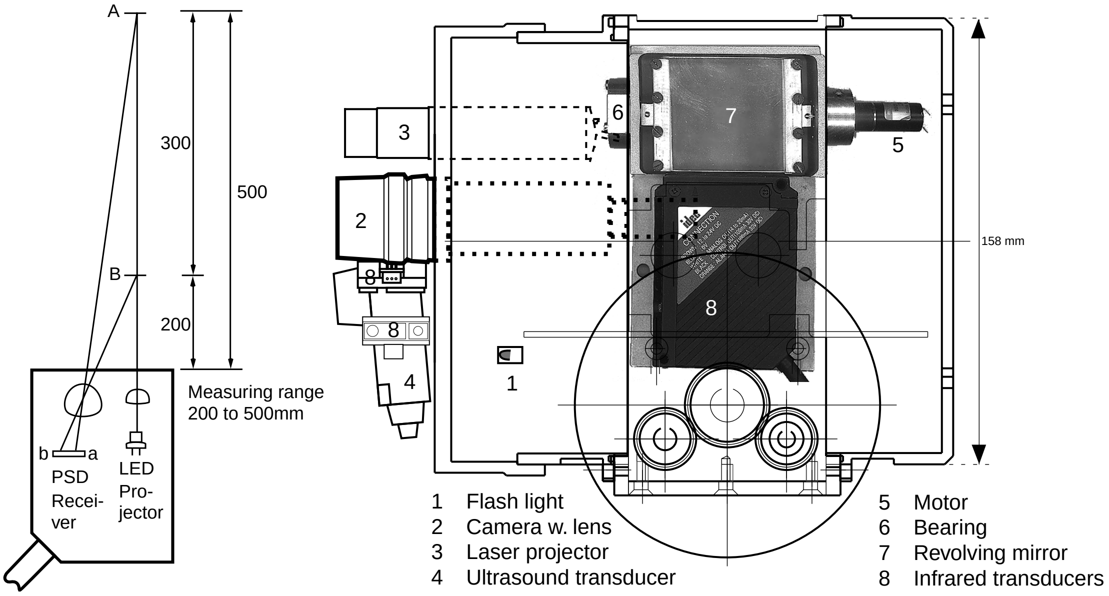
Kuntze and Haffner (1998) describe a device combining structured light projectors and cameras for sewer pipe profiling with the teleoperated KARO robot. KARO has a similarly small head as MAKRO, but the device leaves little space for the other sensors that MAKRO needs for autonomous navigation (cf. figures in section 3).

Alternatively, we propose to scan pipe wall sections for inlets using a cheap custom infrared distance sensor with a high sampling frequency.

## 3 A Custom IR Scanner for Landmark Detection

### 3.1 Sensor Construction

We chose an Idec active infrared distance sensor of type SA1D-LL4. This sensor employs a *position sensitive device* (PSD) and is capable of measuring distances in a range of 20 to 50 centimeters, with the usual limitations of this type of sensor. Figure 4(a) shows a sideview of the sensor's measuring scheme.



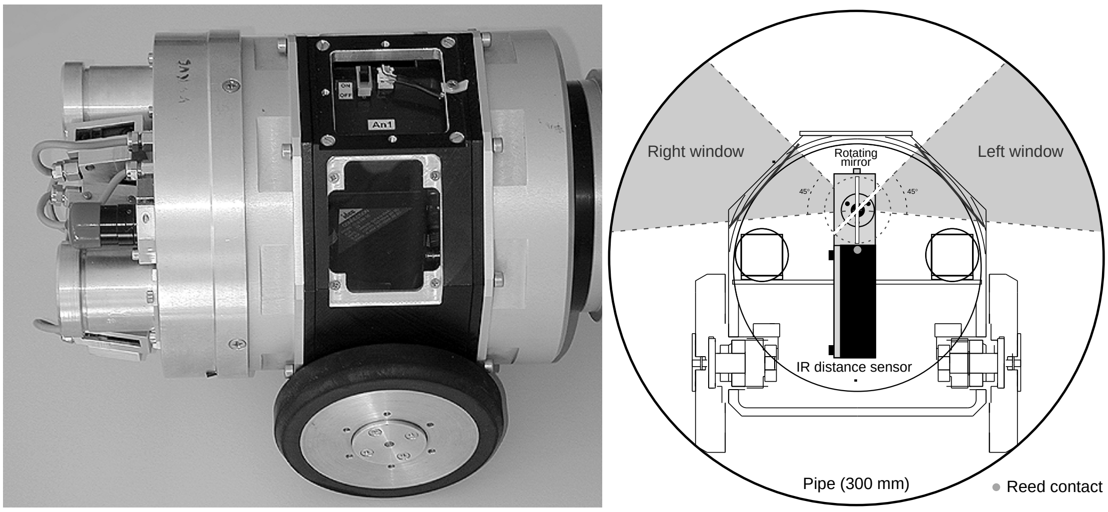
(a) Measuring scheme of IR distance sensor SA1D-LL4.

(b) Construction sketch of MAKRO sensor head (sideview) and photo of rotating mirror device with idec IR sensor (Sketch based on CAD drawing by Inspector Systems Hitzel).

Fig. 4. The custom infrared scanner.

The sensor is mounted in a head segment of MAKRO such that the emitted IR beam points to the top. A double-sided mirror is mounted between the sensor device and the segment top. The mirror is attached to the axis of a small motor (Fig. 4(b)). This axis is parallel to the robot's longitudinal axis.

The IR beam is reflected by the slowly revolving mirror (2 Hz) and repeatedly passes through two small coated glass windows flush-mounted in the top left and right of the end segment's housing. Ideally, enough of the IR beam is reflected and reaches the measuring part of the sensor. Figure 5(a) shows the position of the IR scanner inside one of the robot's sensor heads through a left window.



(a) Front segment of MAKRO 1.1 with sensors. The idec IR sensor is visible through the window.

(b) Schematic front view of scanning range for inlet detection (Sketch based on CAD drawing by Inspector Systems Hitzel).

Fig. 5. Scan windows and scan range.

Sewer inlets are not equally distributed along the pipe perimeter. Rather, they appear in certain known locations, namely in the top left and right of pipes. This allows us to restrict the search area (grey regions in figure 5(b)) and to design the size and position of the windows as described. The small window size also contributes to the stability of the robot case.

### 3.2 Data Selection

The sensor arrangement described in the previous subsection makes the permanently rotating mirror reflect most of the IR beams into the head segment case. Thus we had to distinguish potentially useful data which come from outside the robot from useless data from the interior. We attached a tiny permanent magnet to the mirror carrier. A Reed contact is placed such that it fires when the mirror is in a vertical position. This serves as a reference point. The Reed contact and a special circuit disable the sensor's data output line for a short time, producing a zero value that can clearly be distinguished from measured real data.

Approximately only one fourth of all data have to be interpreted, namely those that come from the robot's exterior. A typical data series for a second, i.e. two full rotations where the IR beam passes both windows eight times—since the mirror is double-sided—is shown in figure 6. For a given scanner mounted in a given end segment, we have to calibrate the interpretation routines in order to filter out useless data that stem from refelections within the robot's case. This is described in the next section.

### 3.3 Scanning Frequency Considerations

One precondition for detecting inlets reliably is that the scan raster must be sufficiently dense for all pipe diameters between 300 and 600 millimeters. If possible, no inlet shall be overlooked while the robot travels at speeds up to 20 cm/s. An ultrasound based scanner is inherently too slow for this task, as a respective investigation revealed (Schönherr, 1998).

Typical inlet sizes range between 10 and 15 cm. To detect such an inlet, the distances between the centers of successive IR beams should not be larger than 5 cm, peripherally as well as horizontally. The largest pipes under consideration, with a diameter of 600 mm, have perimeters of approximately 185 cm. Thus, 37 measurements suffice to achieve the peripheral beam center distance of 5 cm for this class of pipes. For 300 mm pipes, the same number of measurements yields a narrower raster, where the peripheral distance is 2.5 cm. The typical diameter of a beam ranges from 14 mm at a distance of 30 cm to 20 mm at a distance of 50 cm.

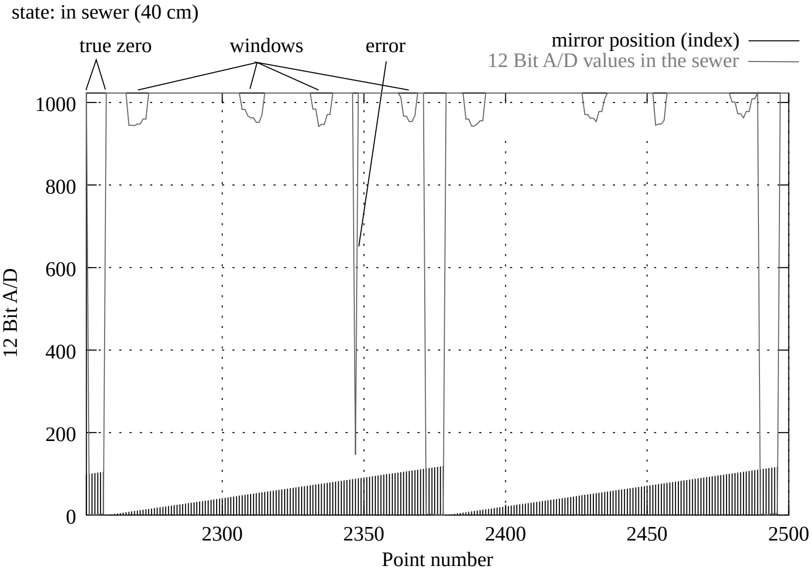


Fig. 6. Scanner measurements during two full mirror rotations. Error peak generated by in-robot reflection. Detection state is “in sewer pipe”.

In order to fully exploit the sensor’s capacity of up to 150 measurements per second, the double-sided mirror may rotate with 2 Hertz, yielding four complete scans per second. Thus, the horizontal beam center distance can be limited to 5 cm simply by limiting the robot’s speed to the typical sewer inspection speed maximum of 20 cm/s (= scan frequency times desired distance).

### 3.4 Data Processing Architecture

MAKRO is steered by a high level control program that runs on a full featured PC/104 operated under Real Time Linux. The PC/104 communicates via CAN bus with seven C167 microcontrollers. The latter ones control the propulsion and joint motors and read the data of most of the internal and external sensors (26 IR distance transducers, two ultrasound transducers, a thermometer, two inclinometers, 15 optical joint angle readers, and more (cf. (Kepplin et al., 1999) for a description of MAKRO’s mechatronic concept).

Sensor readings that are relevant for high level control programs are transferred via the CAN bus to the PC/104. Other sensor data may be processed locally on the C167 microcontrollers. The C167 is fast enough to process the 150 readings of the Idec SA1D-LL4 while performing other control tasks. A specially calibrated evaluation program decides whether the data indicate that an inlet has been scanned. The results are passed to the high level control programs on the PC/104.

## 4 Algorithms and Experimental Results

### 4.1 Auto-Calibration Procedure

As mentioned in previous section, the IR scanner has to be calibrated. In half a second, the rotating mirror turns 360 degrees between two triggers of the Reed contact and sweeps along the two windows. In the linear stream of data recorded during that half second, four interesting regions have to be detected, namely the “positions” of the windows.

For performing the calibration process, the robot is moved outside a sewer pipe such that the scanner detects no obstacles and shows the maximum distance. Figure 7 shows a typical distribution of data collected during a full rotation while the robot is outside of a pipe. The ramp-like spikes at the abscissa are graphical representations of the data indices (cf. below).

In the situation described above, all data measured in a period of five seconds, i.e. during 10 full mirror rotations, are recorded and transformed into a histogram. During the recording procedure, an index variable $i$ is initialized with 0 when the Reed contact is closed, and $i$ is increased when a new measurement arrives. For every measurement it is checked if the digital value lies in the interval of $[100 : 1000]$ and, if so, the histogram value at position $i$ is increased by

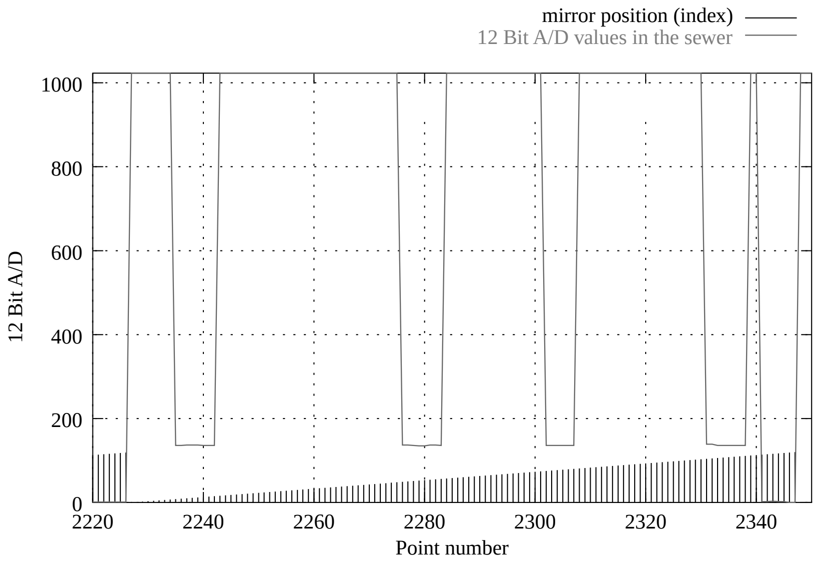


Fig. 7. Measured ranges while robot is outside of a pipe.

one. A typical histogram of the distribution of these measurements is shown in figure 8. Consequently, the positions of the four largest local maxima are selected and the interesting region are adjusted at ±7 index positions around the local maxima (the number ±7 has been determined empirically in our experiments). The obtained intervals, i.e. the regions of interest, are then being used to selectively filter out useless data in further scan operations.

This auto-calibration procedure has to be performed separately for each scanner device, since manufacturing tolerances usually cause slight differences in the index positions of the local maxima.

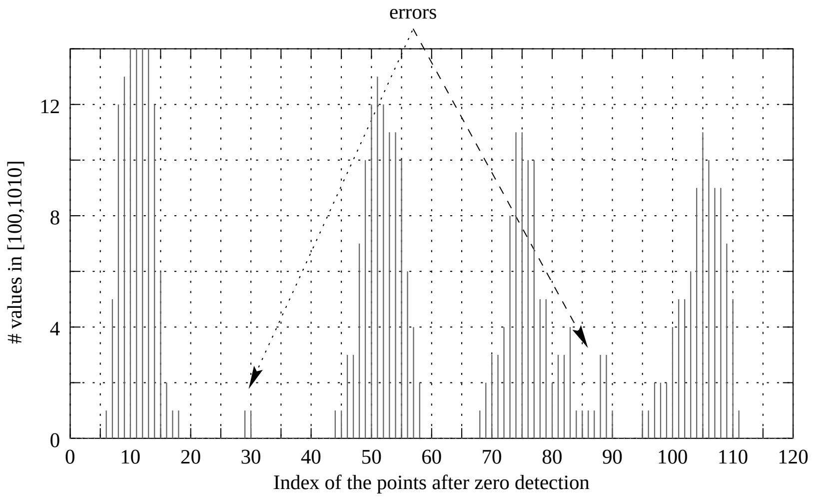


Fig. 8. Data histogram for auto calibration phase.

### 4.2 Scanning Algorithms

While moving through the pipes, the robot scans the environment and should find inlets and other interesting things. The nominal pipe diameter is known and is one of the criteria considered in evaluation of the scan data. Additionally, we have defined five criteria to distinguish detection states of the data that stem from the adjusted regions of interest.

1. the digital value $x_i(t)$ and
2. the minimal value $x_{min}$ in a region
3. the maximal value $x_{max}$ in a region
4. the difference between the current value and the value last turn (t-1), i.e., $x_{diff}(t,i) = x_i(t) - x_i(t-1)$
5. the counted number of values above a threshold $t_{min}$ (= 700)

A higher value of $x_{diff}$ (criterion 4) is an indication that an inlet occurs. A big difference between $x_{max}$ and $x_{min}$ also indicates an inlet, but only if no singular data peak occurs (criterion 5). Singular peaks are more likely to result from errors than from detected inlets.

On one hand, larger inlets lead to many measurements (criteria 1,2,3,5) with large values, whereas on the other hand smaller inlets lead to fewer measurements with smaller values (also criteria 1,2,3,5). With respect to the above mentioned criteria, the robot can distinguish nine different detection states (see table 1).

| State No. | Description | Typical Interpretation |
|---|---|---|
| 0 | no visibility | robot is in the pipe |
| 1 | good visibility to the left side | large inlet on the left side |
| 2 | good visibility to the right side | large inlet on the right side |
| 3 | good visibility to the left and right side | robot is outside of a pipe |
| 4 | small visibility to the left side | small inlet on the left side |
| 5 | small visibility to the left side and good visibility to the right | manhole |
| 6 | small visibility to the left right side | small inlet on the right side |
| 7 | good visibility to the left side and small visibility to the right | manhole |
| 8 | small visibility to the left and right side | small inlets on both sides or manhole |

Table 1. Different states of inlet detection

Ambiguous results, like detection state 8, can be further precised by sensor fusion, i.e. by evaluating the data from the side-looking fixed IR transducers. These sensors can detect branching pipes in manholes, but cannot detect inlets, because their IR beams point to lower regions of the pipe walls where inlets usually are not placed.

### 4.3 Experimental results

We performed several experiments to test the custom scanner in dry sewer pipes. Inlets were simulated by drilling holes in plastic pipes of different diameters (30 cm and 40 cm). Inlet diameters ranged between 10 and 15 cm, inlets were positioned on both sides of the robot head and within the scan angle range.

Figure 9 shows a typical situation where the robot detected a large inlet on its left side in a pipe with a diameter of 40 cm. Depicted data had been recorded during one full mirror rotation. Figure 9 also reveals an error which is filtered out since it is not in one of the four intervals that have been determined during auto-calibration.

We still have to perform a variety of experiments with smaller inlets, inlets that do not lie completely within the scan angle range, inlet pipes with different slopes, and more. These experiments are necessary for fine tuning the evaluation algorithm and for collecting a larger body of data for statistical examination of the evaluation results. However, results look promising, since the scan routines detected every inlet that has been passed by MAKRO in the dry sewer pipes.

Experiments in real wet sewers are still to be performed in order to test the system under target application conditions. These high-risk experiments will be performed not earlier than in the very final phase of system development, trying to delay possible damages of a valuable research prototype as long as possible.

## 5 Conclusion

We have presented a cheap custom built infrared distance scanner for the detection of inlets in sewer pipes. The robust detection of inlets is a prerequisite for reliable self-localization of the sewer robot MAKRO while it is travelling completely autonomously through a sewer net, guided by a net map and steered by an on-board control program that relies on external sensor data.

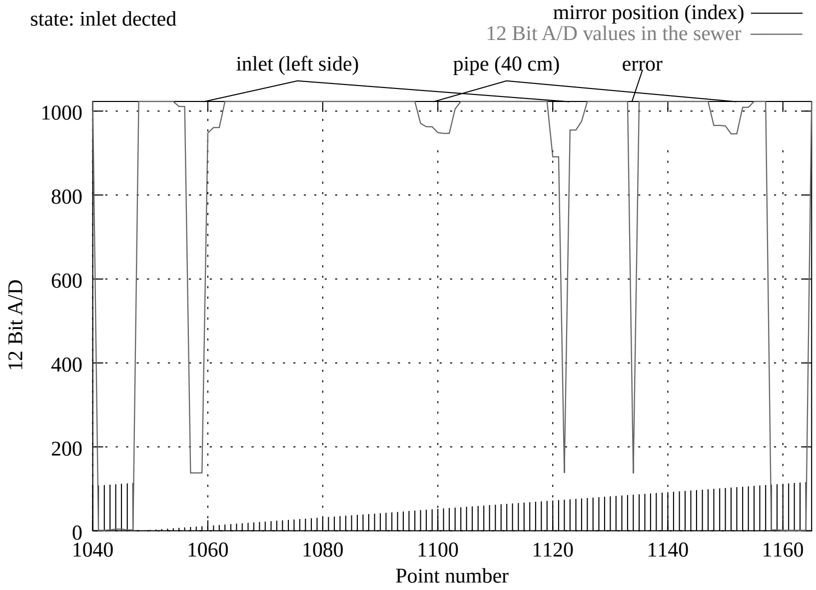


Fig. 9. Detection state is “inlet”.

Although we still have to perform more experiments in order to fine tune the evaluation algorithm, we are confident that after initial calibration, the employed algorithm will work reliably in standard sewer pipes.

The scanner is fast enough to permanently scan relevant pipe sections for the presence of inlets while the MAKRO robot drives at common inspection speeds of up to 20 cm/s. Data evaluation is performed on a C167 microcontroller, and only relevant results are passed to high level control programs.

The presented method is superior to other, ultrasound or vision-based methods, since it is faster and does not require a long training phase. Moreover, the IR scanner is much lighter and smaller than comparable 2D Laser scanners that are available on the market. The lightest system so far—to our best knowledge—, being manufactured by Leuze (2001), is a 14 cm cube of 2.2 kg. Although efforts are being made to shrink Laser scanners, we do not expect to see dramatic improvements in this kind of systems for the next years.

The IR scanner’s small size allows for more sensors and other devices to be integrated into the robot’s sensor heads. The light weight reduces the burden when the robot has to lift its segments in order to climb a step or to overcome a small obstacle. The described custom IR scanner requires less of the robot’s limited on-board ressources—energy, space, computing power—than comparable systems and is appropriate for the task at hand.

## 6 Acknowledgements

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