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Development of Fully Automatic Inspection Systems for Large Underground Concrete Pipes Partially Filled with Wastewater

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 # Emschergenossenschaft

***Abstract*— The Emschergenossenschaft based in Germany is currently planning the Emscher sewer system, arguably the largest residential water management project in Europe in years to come. The Emschergenossenschaft engaged the Fraunhofer Institute for Factory Operation and Automation (IFF) in Magdeburg, Germany, as the general contractor to develop automatic inspection and cleaning systems to meet the requirements imposed by legal guidelines. The systems must operate continuously in a sewer line that has diameters ranging from 1400 to 2800 mm and is partially filled, 25% at minimum, all the time. To construct the Emscher sewer system, the Emschergenossenschaft favors a one-pipe line in long sections. A walk-through or inspection by personnel would be impossible in these sections.**

The Fraunhofer Institute IFF has developed prototypes of all systems for motion through the sewer and all sensor systems, thus achieving a new quality of inspection above and below the water line under these difficult conditions. This article describes significant project results and important components of inspection such as the inspection systems, pipe axis measurement, system positioning, and sensor systems for damage detection.

Fundamental for the development of the inspection systems is the detail of the inspection, which goes far beyond the video inspection common today, and the ability to take comparative measurements throughout the sewer system's period of operation in order to track the development of damage.

I. INTRODUCTION

THE Emscher sewer system has a length of approximately 51 km with expected pipe diameters of DN 1400 to DN 2800 and a depth of 5 to 40 m. The distance between manholes is normally 600 m. The sewer material is reinforced concrete. The sewer line is uncoated and unlined. Even in dry weather, large quantities of water will be discharged into the sewer constantly. Legal guidelines require scheduled, regular and systematic inspection and recording of a sewer system's structural and operational condition. At present, structural condition is usually detected by optical inspection (TV inspection or walk-through inspection). Conventional inspection methods cannot be used to inspect the Emscher sewer system because of its constant partial filling. The automatic inspection and cleaning systems to be designed as part of the project should effectively do away with walk-through sewer inspections. Hence, among other things, approval of the one-pipe sewer will depend on demonstrating that inspection and cleaning can be performed using remote-controlled or automatic systems.

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As part of the project, the following main components were designed and tested for their feasibility and fulfillment of the requirements:

- Carrier system (motion kinematics, robot) for positioning throughout the sewer line
- Sensor and measuring systems for inspecting pipe condition above and below the water line as well as for detecting deposits
- Media supply (power, data communication)
- Control system, operation
- System navigation and positioning in the sewer
- Handling systems for positioning sensors and cleaning tools on and along the sewer wall

A large test station with various reinforced concrete pipes with different types of damage (e.g. cracks or spalling) was set up at the Fraunhofer Institute IFF in Magdeburg. The sensors for inspection were mostly new developments.

In consultation with the Emschergenossenschaft, the Fraunhofer IFF has developed and built prototypes of the inspection and cleaning systems in order to test them in a comparable, existing sewer system with a diameter of 2300 mm. The priority at this time is developing these systeme up to prototype production.

II. INSPECTION STRATEGY

The strategy for automatically inspecting and cleaning the Emscher sewer system entails a three-stage approach.

In the first stage, a small swimming system called the "Spy" is employed in the sewer for a preliminary inspection. It inspects and measures the entire sewer line and conducts camera inspections, recording major abnormalities such as erosion, deposits, obstacles and leaks in the gas space. At the same time, it checks whether the cleaning and inspection systems detailed below can be deployed. In addition, it can be used to quickly inspect sections of the sewer when trouble is suspected. The Spy must be able to position itself centrically even in curved pipes in the sewer covering a length of 600 m.

Fig. 1. Spy system in a real sewer with a diameter of 3600mm

In the second stage, when necessary, the wheel-driven cleaning system eliminates deposits in the bed area detected with the Spy and cleans the sewer wall before the inspection system is deployed.

In the third stage, the wheel-driven inspection system completely inspects the sewer, measuring the sewer (joint widths, pipe offsets, cracks, infiltration, inhibition of flow, corrosion) with greater accuracy than the Spy.

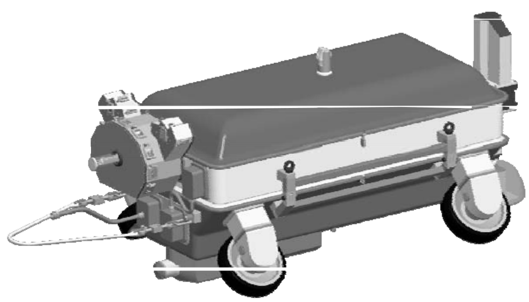

Fig. 2. Inspection system with camera and light sectioning sensor (left), ultrasonic scanner (below) and kinematics with infiltration sensor and ultrasonic sensor for crack detection below the water line

For all three systems, concepts were designed and developed for their control, operation, introduction into and extraction from the sewer line and for their energy and water supply and data transfer.

III. Positioning, Pipe Axis Measurement

Actual position and orientation in the sewer have to be known at the time any measurements are taken by the Spy and by the inspection system. Therefore, pipe axis measurement is an essential prerequisite to an exact representation and analysis of sensor data. To this end, an algorithm was developed, which, taking a model of a complete pipe as its starting point, measures the pipe axis exactly. The total error of pipe axis measurement is arrived at by adding up the accuracy of the laser ranging sensors, the tolerance and the pipe's surface condition as well as the systematic error caused by the Spy system's motion. For the laser and ultrasonic scanners to detect damage, a positional value of the pipe axis has to be assigned for every individual reading. Accordingly, when the accuracy of measurement is being assessed, the superposition of position detection and the measuring method for detecting damage have to be assessed.

In the case of the inspection system, which presses against the sewer wall and remains stationary during measurements, only the laser ranging sensors' accuracy has any bearing on and is the reason for its greater accuracy of measurement than the Spy. A sensor system was conceived, which uses 15 laser ranging sensors (5 aligned vertically and 10 horizontally) to constantly record position. The sensor distance data is transformed into the sensor coordinate system.

To measure the pipe axis, a cylinder with an elliptical surface area is used to model the real pipe with its surface quality and tolerances. This is clearly described in the Spy's coordinate system by the cylinder axis, the radius and the diameter. Interpreting the measurement data would be easy if the Spy were exactly in the center of the pipe without any deviation in its angles of alignment. In reality, the system's tilt, yaw and pitch angles are not aligned with the center of the pipe. The measuring points are not on a straight line but rather on a segment as the green measuring points in Fig. 3 and Fig. 4 indicate. Hence an exact model of the measurement has to be made, which allows for the curvature of the pipe.

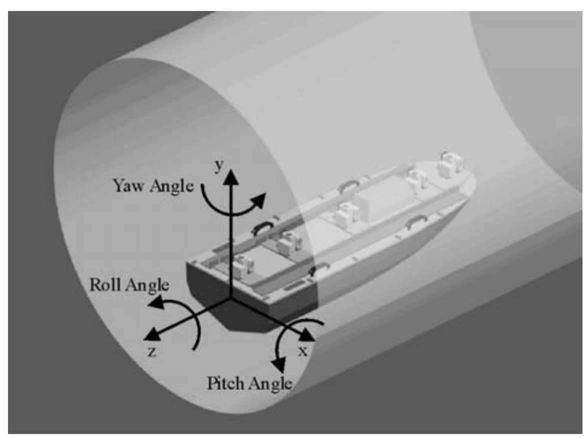

Fig. 3. Coordinate system

The model is based on the correlation between measured distance, pipe radius and displacement to pipe axis as well as yaw and pitch angles. Since this non-linear dependence is known, the alignment of the pipe axis can be determined from the distance measurement. This alignment then makes it possible to transform the measuring points into the circular projection of the pipe and consequently to determine the position of the pipe axis in relation to the Spy and the inspection system. By mathematically resolving the non-linear correlations, pipe position is determined first.

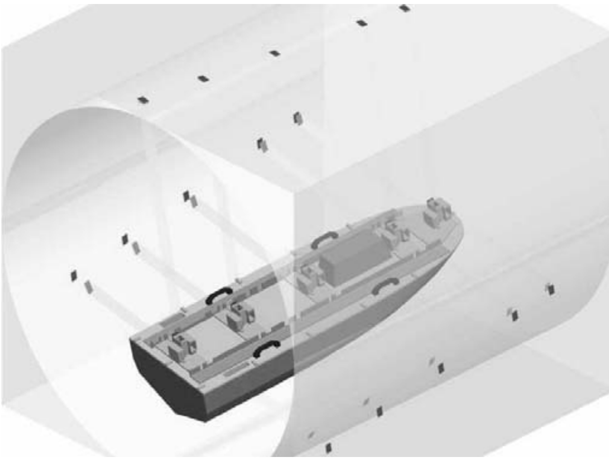

Fig. 4. Difference between the readings in the pipe model (green measuring points) and the model with straight walls (red measuring points)

Determining the position of the pipe axis involves using the pipe axis alignment to plot the measuring points on the circular projection.

After applying this transformation, a circle with an offset center is fit to the measuring points. The displacement of the axis of the pipe in relation to the axis of the Spy is obtained from this fit.

In principle, this approach opens up a method for measuring the pipe axis, which is independent of pipe diameter as well as the orientation and position of the measuring system. This method has a methodological error of zero. Under real conditions though, every system is afflicted by errors. With this in mind, the method was modified so that parable approximations compensate for sensor alignment. Corresponding calibrating measurements are taken on a calibration rig.

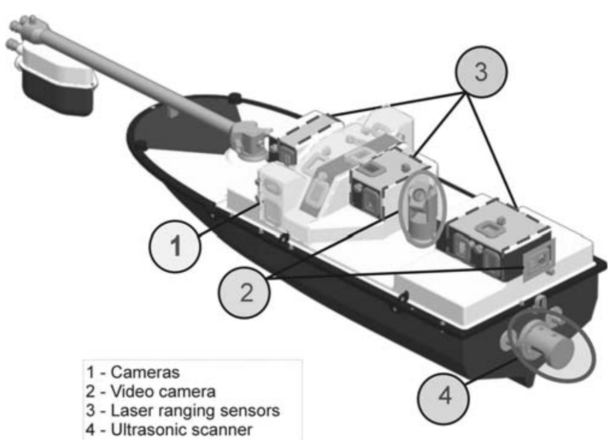

Fig. 5. Sensors on the Spy (final system)

The system's position along the sewer line axis is determined by measuring the lengths of uncoiled cable. In addition, the camera system is used to references current position at all joints. Thus, every single pipe can be dealt with.

IV. Preliminary Inspection System (Spy)

The Spy (Fig. 5) is an easy-to-operate, cable-guided swimming system for preliminary screening of the sewer line. The Spy detects corrosion, obstacles, deposits and cracks.

It detects sewer condition with little operating effort but with less precision than the inspection system. It is deployed in the sewer at a manhole and, guided by a cable, moves with the current in the distance between manholes.

Using a camera system, the Spy can visually inspect the gas space just like the steerable tractors common today. The Spy is additionally equipped with light sectioning sensors for sewer measurement in the gas space and with ultrasonic sensors for sewer measurement in the water space. The Spy prototype must have smooth swimming behavior and lie stably in the sewer line even at higher flow velocity. The objective of the successful navigation tests was to position the Spy centrically in the current in order to create good conditions for geometry measurement. It proved possible to determine the position of the Spy in the sewer and to measure the sewer cross section in the gas space.

V. Inspection Systems

In contrast to the Spy, the distinctive feature of the inspection system is its ability to achieve greater accuracy of measurement with its measuring sensors. Additional sensor systems have also been integrated. Various carrier system concepts were developed. The carrier system concepts for inspection were evaluated using criteria relevant for the user as well as for development and led to the choice of a wheeled-driven system over a floating system.

Sensors for determining position in the sewer (laser ranging sensors and inclination sensors) and sensors for damage detection (laser sensors, ultrasonic scanners, camera system with 8 cameras, light sectioning sensors, ultrasonic crack sensor) were installed on the inspection system. These sensors are either rigidly connected with the carrier system directly or they are moved with additional sensor kinematics. The rotation arm on the stern of the inspection system moves the ultrasonic crack sensor along the sewer wall. Ultrasonic scanners, laser sensors and camera system are mounted on the inspection system and measure the pipe profile.

VI. Types of Damage and Selected Sensor Systems for Damage Detection

One focus of the project was developing the sensor systems, which have the accuracy of measurement required under difficult conditions in the sewer and make it possible to take comparative measurements throughout the sewer's period of operation (120 years).

Minimum requirements for sewer inspection in Germany are stipulated in self-monitoring regulations issued by the individual states. Legal requirements, technical specifications and negotiations with local authorities have produced the inspection tasks displayed in table 1. The requirements of a one-pipe line are far more demanding than those in the technical guidelines.

TABLE 1
INSPECTION TASKS FOR THE INTERCEPTORS PARALLEL TO THE EMSCHER SEWER SYSTEM

		Accuracy	Detection Necessary	
Damage	Damage Specification		Gas Space	Water Space
Chemical corrosion (gas space)	Corrosion on pipe walls and pipe connections	Loss of material/ differentiation between - smooth pipe wall - rough pipe wall - visible gravel, - eroded gravel - visible reinforcement (comparison with previous inspections)	Yes	No
Mechanical corrosion (water space)	Erosion	Loss of material (10 mm) (comparison with previous inspections)	No	Yes
Inhibition of flow	Obstacles, sediments, incrustations	5% of sectional area	Yes	Yes
Translation	Horizontal/ vertical	± 8 mm	Yes	No
	Axial	± 5 mm	Yes	No
Cracks	Longitudinal/ radial	> 0.5 mm	Yes	No

A. *Chemical Corrosion*

Optical measuring methods detect surface corrosion of the concrete in the gas space and indicate possible developing damage. A semi-automatic procedure consisting of automatic and manual analysis performed by an operator is favored for corrosion detection and classification. The important option of comparing the concrete wall with previous inspections facilitates the representation of the development of damage. Several cameras are used to completely map the sewer wall.

An image processing algorithm with a short runtime is used to detect abnormalities instantaneously. The appearance of individual surface structural elements is inspected for abnormalities, the number measured being more important than its precise characteristics. When a variable limit value is exceeded, surface corrosion may be likely.

Direct statements can be made about the potential occurrence of corrosion by comparing the distribution of the various proportions of gray tones in the readings with calibrated values or values already ascertained from previous inspections.

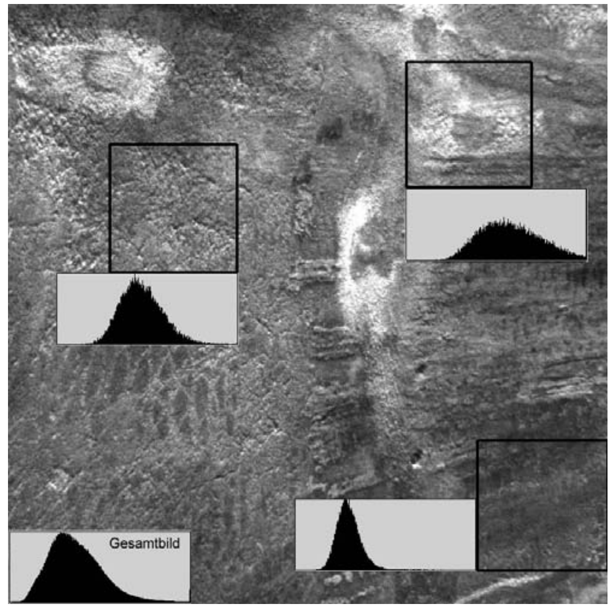

Fig. 6. Image of a corroded concrete surface with superimposed gray scale curve for subareas

Fig. 6 shows the various curves for differently corroded surfaces. Differently damaged subareas can be identified clearly and individually. A total assessment of potential corrosion can be obtained by averaging the entire image space.

B. *Obstacles, Sediments, Incrustations, Mechanical Corrosion*

Newly developed ultrasonic scanners with an accuracy of measurement of +/- 2mm are used to detect obstacles, deposits and mechanical erosion in the water space. Figure 7 presents obstacles with a maximum resolution detected by the inspection system at a standstill.

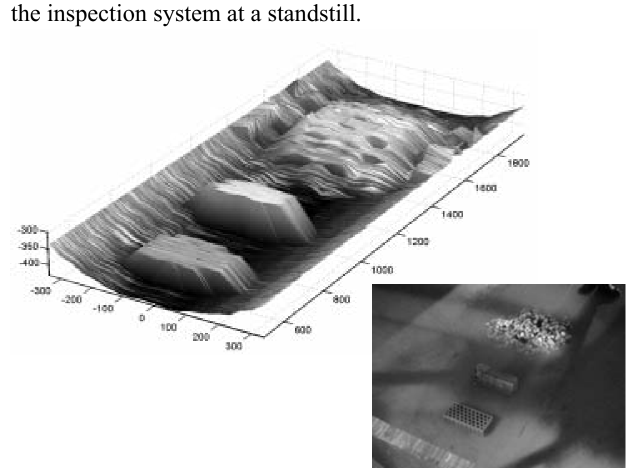

Fig. 7. Geometry measurements taken with the ultrasonic scanner (obstacles, sediments)

Fig. 8 shows a section of the sewer line during a series of tests with the Spy. Its swimming motion makes it impossible to achieve the same accuracies as the inspection system. Obstacles >10mm can be detected of course.

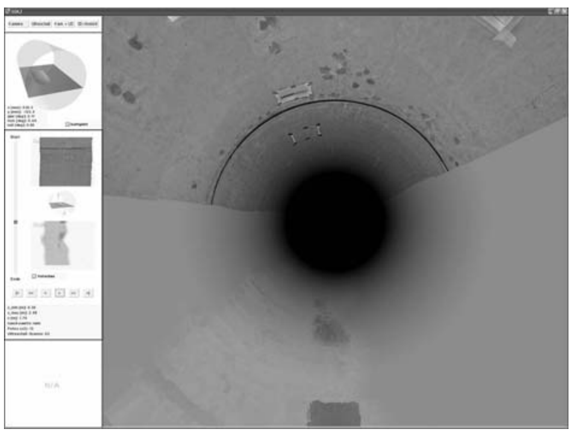

Fig. 8. Obstacle detection with the Spy (obstacles are colored red)

C. Crack Detection in Concrete Pipe

Digital image processing systems are used to detect cracks in the gas space. Several cameras are used to do this.

In accordance with the requirements, cracks with a width of 0.5 mm and upward have been positively identified and logged. As opposed to corrosion detection, which has to identify large-area damage, crack detection involves small features. While cracks can reach a long length, their frequently very narrow width makes great demands on the measuring system mapping them. Other measures such as comparisons with previous inspections and images of other cracks with known widths as well as the superimposition of scales facilitate more precise determination of crack width and thus more precise identification of the type of damage.

An important analysis module is automatic crack detection. It employs methods of image processing and pattern recognition to determine whether or not one or more cracks might be visible on a particular image. This automatic system constitutes a considerable advantage and increases the quality of the inspection results, especially when cracks are small ones an operator could overlook on the monitor.

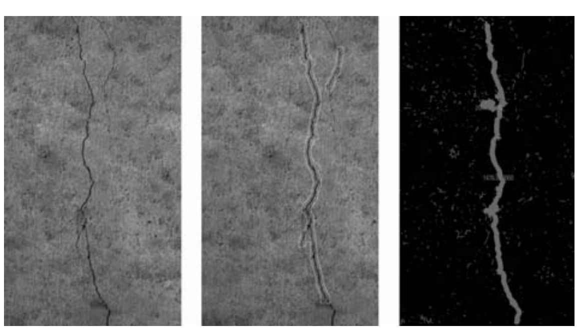

Fig. 9. Details of result images when different crack detection methods are employed

Fig. 9 illustrates crack identification by different analysis modules. Each crack was additionally highlighted as a recognized structure for the purpose of presentation. The course of the entire crack was never identified. However, information about whether or not a crack may be present in a particular image is an important support for users. The automatic analysis module can even terminate the processing of the current image and inform the user when any crack segment has been detected.

D. Deviation of Position

Horizontal and vertical deviations of position and joint gaps have to be measured. Laser scanners aligned laterally or on the apex of the sewer are used to detect and log the horizontal and vertical deviations of position.

Cameras measure the joint gap in the gas space. Differences in joint width compared with earlier inspections indicate axial displacement; inconstant joint width along the pipe circumference indicates deformation.

Automatic measurement requires precisely identifying joint edges. To this end, image processing methods determine the pixels on the edges of the joint.

Fig. 10a presents a detail of the identified pixels. When the parameters have been selected properly, joint edges can be identified with an accuracy of a few pixels. Applying these pixels in ellipse approximations to optimally approximate the number of points produces the joint edges, which in turn support automatic measurement of the joints. This procedure compensates for fluctuations generated by the pixel raster and irregularities or damage along the joint edge.

Fig. 10b is a detail of the joint image with such ellipse approximations.

A Hough transformation can be used to determine the ellipse approximations. Since positioning and joint identification already identify the joint edges, the parameters of the corresponding ellipses are also approximately known. Thus, the search area of the Hough transformation can be greatly restricted, making efficient implementation possible.

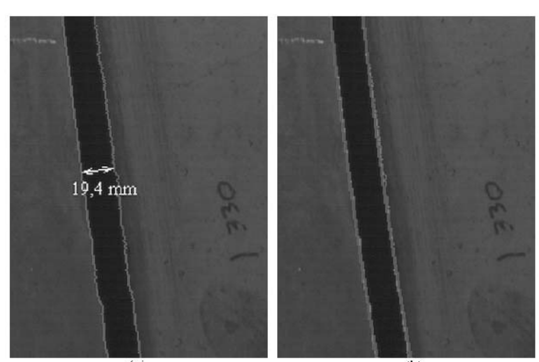

Fig. 10. Image detail with detected joint edges: Manual measurement marks a joint by hand (a). Automated joint measurement marks joint edges with ellipse approximations (b)

VII. Summary and Outlook

As general the contractor, the Fraunhofer IFF has developed a comprehensive concept for inspection and cleaning systems for the Emscher sewer system. Not only have all the relevant subsystems been specified but they have also been designed in detail and subjected to all tests needed to provide reliable information about their feasibility. Their feasibility has been fully demonstrated. Foci of development have been carrier systems for movement through the sewer line, which guarantee maximum recovery certainty, pipe axis measurement and system position sensing in the sewer, and sensor systems for detecting condition in the sewer's gas and water spaces. Different sensor systems have been developed and tested at the test station in Magdeburg as well as in a real sewer. Erosion, incrustations and corrosion of concrete are detected with great accuracy. Cameras detect axial displacement and laser scanners detect offsets in pipe joints in the gas space. Apart from the cameras, different sensors for crack detection in the gas and water spaces have been developed on an acoustic basis (e.g. ultrasound).

Along with the sensors, all systems have been designed for the favored inspection and cleaning concept. This involved a system for preliminary inspection of the sewer (Spy) as well as cleaning systems and inspection systems. The control, the operation, the introduction into and extraction from the sewer and the manhole have been engineered as has the energy and water supply and the certainty of recovery has been guaranteed in case of malfunction.

The feasibility of automatic inspection and cleaning systems for the Emscher sewer system and the fulfillment of the legal requirements for inspection and cleaning have been demonstrated. The research on and tests of the inspection systems, the sensor systems and the cleaning technology guarantee the one-pipe sewer line will be inspected and cleaned as required by law.

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