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Concept and Design of A Fully Autonomous Sewer Pipe Inspection Mobile Robot “KANTARO”

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Abstract— **In current conventional method, the sewer pipe inspection is undertaken using a cable-tethered robot with an on-board video camera system, completely, tele-operated by human operator. All commercial sewer inspection robots have platforms with poor mobility functions so that those robots are only capable to move into the straight pipes. Inspecting the sewage pipes using the state of the arts inspection methods by the current robots is costly, mostly human cost, and not fast enough to check and inspect the amount of sewage pipes will grow stronger than it has actually happened, specially in Japan. In order to realize inexpensive and effective inspection system, an autonomous pipe inspection method should be introduced to improve the inspection efficiency by reducing the time and manpower in the inspection process. The development of a fully autonomous pipe inspection system, requires design and development of an un-tethered mobile robot equipped with the required sensors using for autonomous pipe assessment and damage detection, and capability of navigating, completely, autonomously inside of sewer networks including different types of pipe-bends such as curves and junctions. KANTARO, presented in this paper, is the prototype of a passive-active intelligent, fully autonomous, un-tethered robot which has an intelligent modular architecture in its sensor and mechanism. KANTARO prototype robot, including a novel passive-active intelligent moving mechanism, can move into the straight pipe and pass various kinds of pipe bends without need to any intelligence of the controller or sensor reading. In order to realize a fully autonomous inspection robot, we also developed a small and intelligent 2D laser scanner for detecting of the navigational landmarks, independently with the main computer system, and fusion with a fish eye camera to assess the pipe state and fault detection.**

I. INTRODUCTION

Sewer systems are prone to damage due to aging, excessive traffic, geological change, earthquakes and chemical reaction. Due to these damages, the groundwater is increasingly contaminated. Furthermore, heavy rainfall events my lead to inroad of the systems, resulting in overflow. In the case of separate sewer system as widely present in Japan [1], this results in the undesired mixture of waste water and rainwater. In addition, sewage may leak out, possibly polluting soil and ground water, and it may wash away soil, possibly eroding the foundations of buildings or the underground of streets and pavements. Thus, in order to ensure an optimal functioning sewer system, extensive inspection in necessary. In current conventional methods, the inspection of sewer pipes is carried out using a cable-tethered robot with an on-board video camera system. The inspection team members insert the inspection robot into the manhole (definition of manhole has been specified in the next section). Following these preparations, the inspection camera with the platform is remotely operated by human operator (Fig. 1). Detected damages are then manually recorded onto standard video tape. All equipment necessary to supply and control the robot are arranged inside of a car, out of the manhole, which causes a heavy and stiff cable for the robot. In addition, all commercial sewer inspection robots have a poor mobility function to pass any kind of pipe-bends such as curves and junctions so that those robots are only capable to move into the straight pipes. These two main reasons, “heavy and stiff cable” and “poor mobility function” cause that, in most case, after the inspection of a pipe line in between two

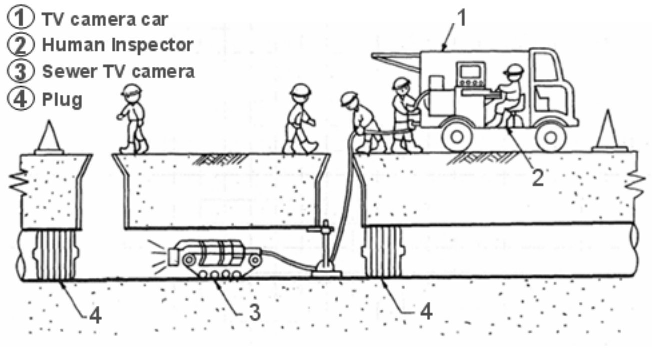

Fig. 1. In current conventional method, the inspection of sewer pipes is undertaken using a cable-tethered robot with an on-board video camera system. An operator remotely controls the movement of the robot including a video system [2].

manholes the robot has to be pulled back, the equipment disassembled, relocated to the following manhole and set up again. This method for inspection of the sewer pipes makes the inspection process very slow (300 meters a day) and costly (1800 yen/16 dollars per meter) in Japan [1].
In order to realize inexpensive and effective inspection system, an autonomous pipe inspection method should be introduced to improve the inspection efficiency by reducing the time and manpower of the inspection process. The development of a fully autonomous pipe inspection system, requires design and development of an un-tethered mobile robot equipped with the required sensors using for autonomous pipe assessment and damage detection, and capability of navigating, completely, autonomously inside of sewer networks including different types of pipe-bends such as curves and junctions. In this paper we propose an innovative, fast and robust sewer inspection robot called "KANTARO" which fits to the pipes within a diameter range of 200-300 millimeters. KANTARO, including a novel passive-active intelligent moving mechanism (named naSIR mechanism), is able to move into the straight pipe and passes different kinds of pipe bends without need to any intelligence of the controller or sensor reading. In addition to realize a fully autonomous inspection robot, we developed a small and intelligent 2D laser scanner for detecting of the navigational landmarks such as manholes and inlets as stand-alone system and fusion with a fish eye camera to assist the pipe state and fault detection.

II. GENERAL CONSIDERATION

A. *Different qualitative degrees of autonomy in sewer robots*

The exact definition and description of "autonomy", related to the sewer maintenance robots, can lead us to compromise what are the necessary required sensors, hardware and computing equipments for developing an fully autonomous mobile robot (described in next sub-section). In general the degree of autonomy in developed inspection pipe robots is classified as follow:

No autonomy: The robot is completely tele-operated, usually via a tether cable, by a human operator. The pipe condition is assessed by the human operator who watches the sensor data (usually video) as the robot drives through the pipe. Mostly all the commercial sewer inspection robots are not autonomous system.

Semi-autonomy: The tethered robot is partially controlled by automatic control programs and modules, or the assessment of the pipe condition is partially performed by sensor data interpretation programs. There is a number of researches and developments of the robots with the semi-autonomous function capability, e.g., "PIRAT" for the quantitative and automatic assessment of the sewer condition [3], "Pipe Rover/Pear Rover" for water filled pipes and ducts developed in 1996 [4], [5], and "KARO" as a cable-tethered carrier for sewer inspection and testing sensory equipment [6], [7].

Full autonomy: The un-tethered robot carries all required resources on-board. Navigation is performed completely by control programs running on on-board computing equipment. Status messages may be communicated to a human inspector over a radio link. Assessment of the pipe condition may be performed partially on-board, or offline after retrieval of the recorded sensory data. A few research have been done in development of a fully autonomous mobile robot for pipe inspection. "KURT"[8] and "MAKRO"[9] are two robot platforms[1] were designed for autonomous navigation in roughly cleaned sewer pipes with in diameter range of 300 to 600 millimeters at dry weather condition in Germany. KURT with capability of turning at ground level pipe junctions was designed for autonomous navigation in a test field with a specific map data loaded to the robot from start to the goal. MAKRO's case design, consisting of six segments connected by five motor-driven active joints, allows for simultaneously climbing a step and turning in the pipe junctions. The goal of the MAKRO project was to prove that a robot is able to navigate completely autonomously inside sewer pipes under the above mentioned condition.
The degree of development of complete autonomous sewer robots presently does not warrant to use them safely and robustly in sewers. Most of these robots have a complex moving mechanism and multi-sensor equipment for navigation and motion control. These complexities in mechanism and data processing make not easy to realize reliable commercial products specially for small range of the pipes up to 300 millimeter in diameter.

B. *Difficulties of developing a fully autonomous inspection mobile robot*

Fully autonomous sewer robots must include sensors for their own control, navigation and localization, not only those for sewer state assessment and damage detection. In addition, localization is an issue not only for the proper robot control, so that the robot knows where it is, but also for inspection, as detected damages have to be reported with their location. In this concept, navigation and localization for the sewage inspection robots, as a whole, can be classified in two main groups: "Motion-Navigation" used for control of robot locomotion and "Fault-Navigation" applied for reporting the location of happened faults in the pipe interior. Consequently, the robot sensory system should be consisted of three groups of sensors: inspection sensors for gathering the pipe state information, sensors for Fault-Navigation, and sensors using in Motion-Navigation. The sensors used for motion-navigation may overlap with the inspection sensors (e.g. a camera may be used for both motion-navigation and damage detection). Motion-navigation sensors, mostly, should mounted in the front side of the robot that it makes complex design to avoid the overlapping of their workspace with the workspace of sensors using for inspection and fault-navigation. As a summary, the necessary requirement to design a fully autonomous inspection mobile robot can be itemized as follows:

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[1] Using the term "platform" means to emphasize the fact that the respective systems do not include sensors for finding damages or assessing the pipe state, but just sensors to warrant their safe navigation and control. Such pipe-related sensors maybe be implemented on autonomous platforms.

- An un-tethered robot must carry ***all required resources on-board***.
- ***Motion-Navigation*** must be performed completely by control programs running on on-board computing equipment.
- ***Assessment of the pipe condition*** and ***Fault-Navigation*** may be performed partially on-board, or offline after retrieval of the recorded sensory data.
- Status messages may be ***communicated to a human inspector*** over a radio link.

All the necessary hardware, robot platform, sensors, and computing equipment should be designed and selected based on the above requirements satisfaction.

C. An overview to the sewer pipe system in Japan

In Japan mostly 85% of the sewer pipes are under 600mm diameter and mainly more than 65% of this amount have a diameter within range of 200-300mm [1]. In this range of pipes, a sewer pipe net is constructed, mostly, by combination of pipes, pipe bends, manholes, pipe joints and inlets (Fig. 2). In general, any changing in the direction of a pipe or any intersection between two or more pipes are called pipe-bends. Pipe-bends in a sewer, as a whole, can be classified in two main types depending on their constructions and shapes: Curves and Junctions. According to the sewer pipe construction lows in Japan, there is a manhole at the beginning of the pipe lines, between each 50 meters pipe and over all pipe bends. In addition, the sewer pipe net is constructed in such a way that the all pipe-lines have at least 3 degrees slope with respect to the horizontal level, because of necessity of flowing water in one direction in a sewer network. A pipe joint is formed in the connection surface of two straight pipes and an inlet is used for connecting a house pipe to a main pipe.

III. KANTARO ARCHITECTURE

KANTARO is designed as a fully autonomous, un-tethered robot, which fits to the pipes within a diameter range of 200-300 millimeters. KANTARO's autonomy and its kinematic abilities extend its potential mission range enormously, comparing to conventional inspection equipment that is limited by the cable and poor kinematics. KANTARO carries all the necessary resources on-board. Standard lithium polymer batteries provide the power for its 4 motors, the sensors, the light and electronics, including a developed computer system and an optical underground wireless communication module, allowing for an autonomous up time of about one hour. To realize a reliable, robust robot and an easy maintenance system, KANTARO is designed to have a complete modular architecture in its mechanic, hardware and software. KANTARO, as shown in (Fig. 3), consists of two main modules: Bottom and Upper box modules. Bottom box, including a passive-active intelligent mechanism (naSIR mechanism) and a battery pack, can be presented as a robot platform. Electronic boards, the sensors and light are installed in upper box which be connected via the main connector to the bottom box. In addition, KANTARO has IP67 waterproof standard that it achieved by waterproof design of kANTARO's modules including the upper and bottom box, motor boxes and battery pack.

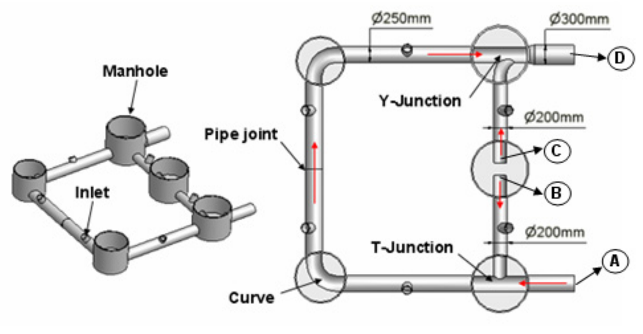
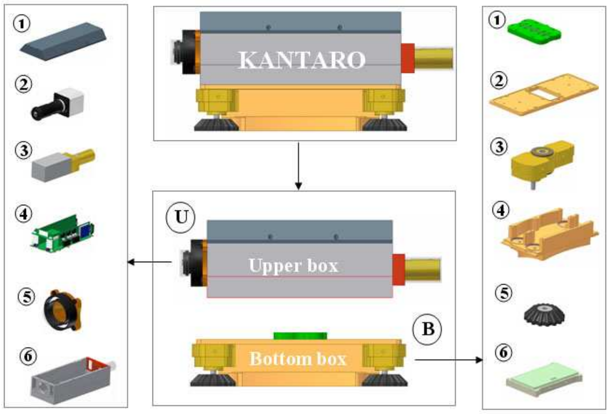


Fig. 2. An example of a network of sewage pipes, in Japan, within a diameter range of 200-300 millimeters. Red arrows show the direction of water flow into the pipe net.



	Full name		Full name
U	Upper box	B	Bottom box
U-1	Upper box cap	B-1	Main connector
U-2	Camera	B-2	Bottom box cap
U-2	Laser scanner	B-3	Motor box
U-2	Hardware	B-4	Bottom box base
U-2	Light	B-5	Wheel
U-2	Upper box base	B-6	Battery pack

Fig. 3. KANTARO has a modular architecture consist of two main modules: Bottom box and Upper box. Modularity of bottom and upper boxes showed in right and left of the figure, respectively.

A. KANTARO platform (naSIR Mechanism)

With regard to the current sewer pipe inspection technology, all commercial robots are capable to move in straight pipes but not any kind of pipe-bends. In addition, current sewer inspection robots are not able to pass different size of pipes. However, because of the large number of pipe-bends in the sewage pipe network, specially in Japan, pipe-bends pose one of the biggest issues for these kinds of robots. Design a robot that can move into the straight pipes and pass pipe-bends will be a great industrial progress in sewer inspection industry. Same as MAKRO case, introduced in introduction, there is a number of efforts and researches to develop multi joint (snake-like) robots with capability of passing curves and junctions [10], [11], [12]. Most of these

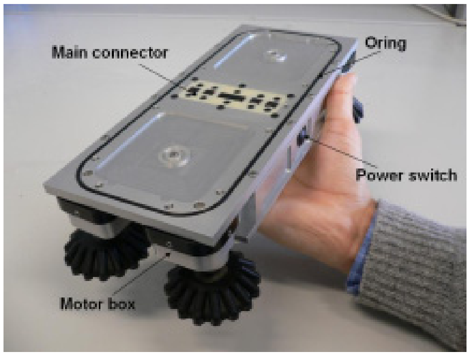


Fig. 4. KANTARO platform (Bottom box module) consists of naSIR mechanism, a lithium polymer battery pack and a power switch.

robots have a complex mechanism and several sensors for detecting the pipe bends and pass them. These complexities in mechanism and data processing makes not easy to realize reliable commercial products.

In this section we describe a special patented mechanism for KANTARO called “naSIR Mechanism” [13]. naSIR is a passive-active intelligent, compact and novel moving mechanism that can move into the straight pipes and passes different kinds of pipe bends without need to any intelligence of the controller or sensor reading. This passive-active mechanism as a KANTARO platform (bottom box module, Fig. 4) itself can move into the pipe and passes wide variety of the pipe bends even without controller for the wheels actuators (without upper box module). In addition, this moving mechanism has capability to pass the different size of pipes in diameter even from a bigger diameter pipe to smaller diameter and also can pass a small obstacle and go down a small step.

The design is based on the concept “passive adaptation of robot wheels to the bends in the pipe”. This is accomplished by proper wheels orientation and passive damping of springs.

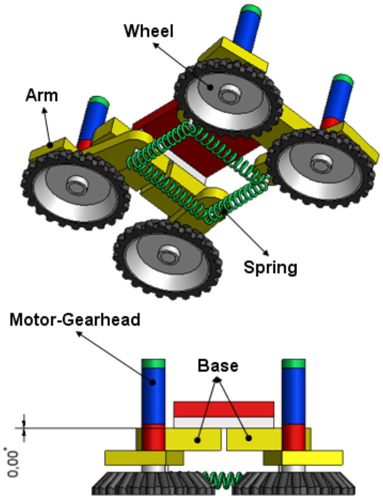


Fig. 5. naSIR mechanism has four wheels parallel with horizontal level which are connected to the four arms and each arm is jointed to the base plate, independently, and they connected to each other by using four springs.

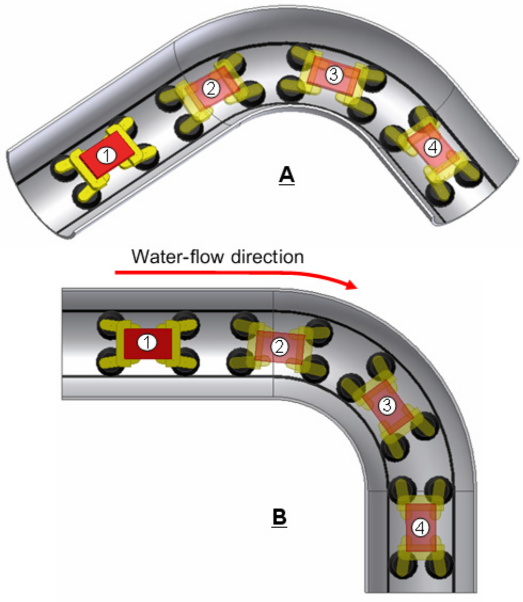


Fig. 6. naSIR mechanism motion during passing a 90 degree curve (A: Top view, B: 3D view). Robot can adapt itself into the pipe interior to have a continuous movement on the optimum path-line (black line).

naSIR mechanism, where as most of inspection robots have a moving mechanism with four, six or more vertical wheels (car_like robots), has four “horizontal” wheels connected to the four arms and each arm is jointed to the base plate, independently, and they connected to each other by using four springs (see Fig. 5). naSIR mechanism, including this special and simple suspension system, has a smooth and robust movement while passing a curve or junction. In naSIR mechanism, the contact positions between the wheels and pipe-wall relative to the robot are steadily the same, thus it can move through the different degrees of the pipe curvature smoothly without any control and sensor reading (e.g. a 90 degree curve, shown in Fig. 6). Moreover, while the robot moves through the curve, there is a contact point on each of the four wheel circumference which at each moment in

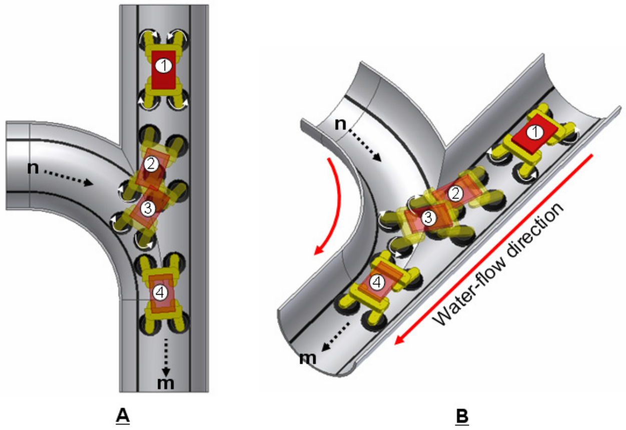


Fig. 7. naSIR mechanism motion during passing a Y-Junction (A: Top view, B: 3D view). The white arrows indicate the direction of wheels rotation.

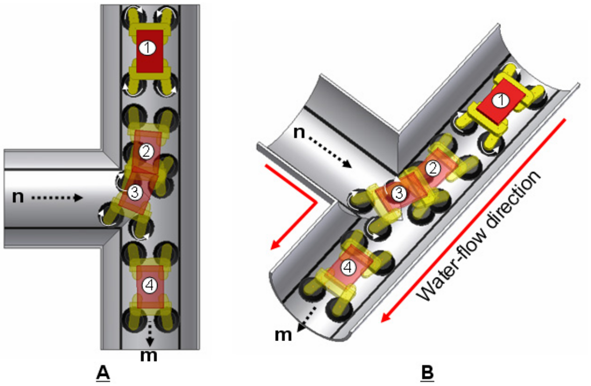


Fig. 8. naSIR mechanism motion during passing a T-Junction (A: Top view, B: 3D view). The white arrows indicate the direction of wheels rotation.

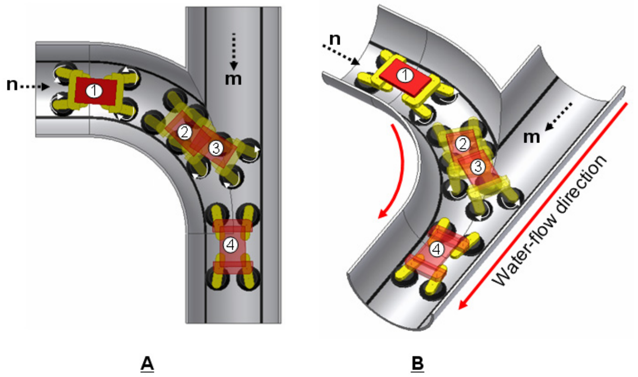


Fig. 9. naSIR mechanism motion during turning in a Y-Junction (A: Top view, B: 3D view). The white arrows indicate the direction of wheels rotation.

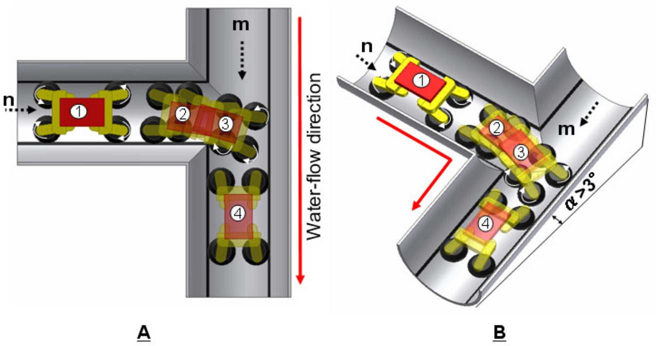


Fig. 10. naSIR mechanism motion during turning in a T-Junction (A: Top view, B: 3D view). The white arrows indicate the direction of wheels rotation.

time has exact similar condition relative to the robot so that it can be encircled by the pair of optimal path-line (black line), as shown in Fig. 6. Figures 7 and 8 illustrate the robot movement toward the direction (m) while passing a Y-junction and T-junction, respectively. The white arrows, in these figures indicate the direction of wheels rotation. In both cases, because of specific surfaces formed in the junction intersection, first the robot starts to turn toward the direction $(-n)$ (robot position #2), but immediately upon the contact of the right front-wheel with the optimal path-line (robot position #3) the robot corrects its path and moves forward in the direction (m). Consequently, as the same reasons mentioned in above, the robot can turn toward the direction (m) when the robot motion started from a branch-pipe located in direction (n) of a Y-junction or T-junction as shown in Figs. 9 and 10, respectively. Note that in case of T-junction, because of the pipes slope, the robot, in position #2, has the tendency to turn toward the direction (m). Figure 11 indicates the naSIR mechanism movement when it is moving from a bigger diameter to smaller diameter pipe. In addition, naSIR mechanism, because of its special morphology, has an intelligence in selecting the correct direction of its movement same as water-flow direction with no control or sensor reading. Comparison of the water-flow direction shown with the red arrows in Fig. 2 and the direction of the robot motion in Figs. 6 to 10 can lead us to easy understanding of this fundamental and significant point in naSIR mechanism. Moreover, as an example, if the naSIR mechanism is inserted from point (A) or (B) or (C) to a sewer pipe network shown in Fig. 2, naSIR mechanism can reach to the point (D) independent of which location is selected as an entry point, with no requested sensor or control. naSIR mechanism was improved by changing the wheels orientation from 0 degree to 5 degrees with respect to the horizontal level (Fig. 12).

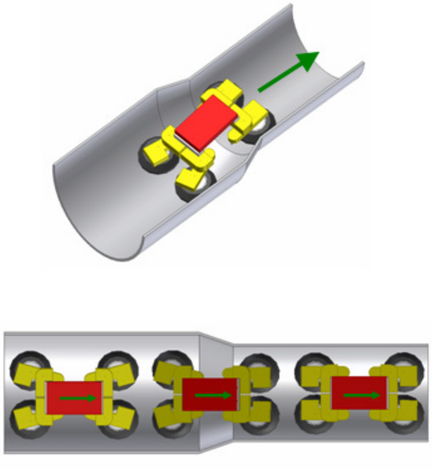


Fig. 11. Motion of naSIR mechanism when it is moving from a big diameter to small diameter pipe.

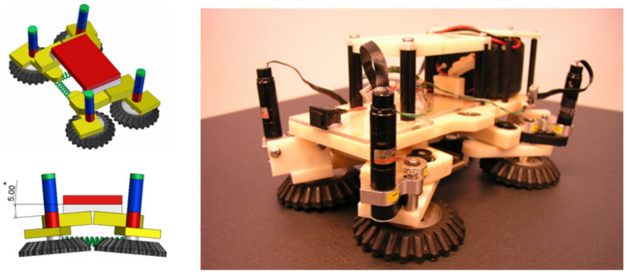


Fig. 12. First prototype of naSIR mechanism. naSIR mechanism was improved by changing the wheels orientation from 0 degree to 5 degrees with respect to the horizontal level.

In this approach, KANTARO has a more smooth motion in T-junctions and also it is capable to move on the flat surfaces.

B. KANTARO hardware

We designed all necessary electronic boards used for control, saving sensory data and wireless communication as a module, called E.B. module, fit to the upper box of KANTARO (Fig. 13). E.B. module contains a mother board, power and motor controller and CPU boards, hard disk and an optical underground wireless communication board. All boards are designed as separated modules to communicate to each other via their own connectors through the mother board. In the newest version of E.B. module, power board and hard disk are combined with mother board to be a more compact and wiring less module. Wiring less was one of our target in this project to realize a compact, reliable and robust hardware for KANATRO. To achieve the wiring less electronics, KANTARO hardware is designed base on modular architecture. Table I illustrates the specification of KANTARO electronics boards.

C. KANTARO sensors

KANTARO's sensor system includes an intelligent laser scanner, one fish eye camera, two IR sensors and an inclination sensor. The first two sensors are only used for inspection and fault-navigation, because KANTARO, including naSIR mechanism, dose not request any kind of sensor for motion-navigation. In this approach we had no constraint for mounting the sensors, mentioned above, into the upper box of KANTARO. Using an inclination sensor mounted on the mother board, and on-board control program, KANTARO is able to automatically correct for tilt in its pose when driving inside a sewer pipe. To avoid driving the robot in a step down more than 10 [cm] and protection from obstacle, two IR sensors are installed in front of robot in two side of the camera. Figure 14 illustrates the arrangement of KANTARO sensors. Rotating laser scanner has been developed as a small and intelligent sensor installed in the robot rear to scan radially the inner side of a pipe wall. If the KANTARO moves along the pipe while measuring, the laser beam measures along a spiral on the pipe inside, where the resolution of the spiral depends on the turn rate of the reflection and the speed of robot (Fig. 15). To reduce the data processing on the E.B. module, the developed laser scanner is improved to detect the navigational landmark such as

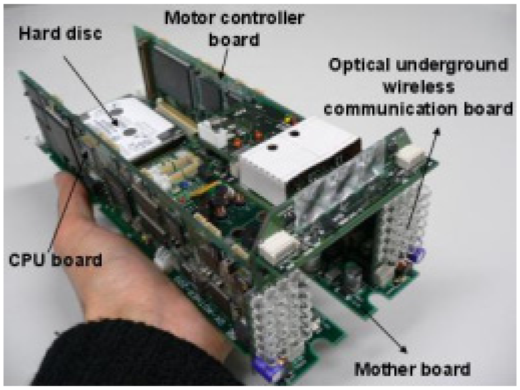


Fig. 13. The newest version of KANTARO electronic boards module (E.B. module)

TABLE I

KANTARO ELECTRONICS BOARDS SPECIFICATION

CPU board		Motor controller board	
CPU	SH7750R(SH-4)	**CPU**	SH7055R(SH-2E)
FPGA	EPF10K100AGC484	**FPGA**	EPF10K100AGC484
Memory	SDRAM 512k×2	**Memory**	SDRAM 512k
I/F	RS232c, LAN	**I/F**	RS232c, CAN
Image compression	ADV202	**I/O**	PWM×5,PIO (8×2)
video input	NTSC		
Size	215(L)*55(H)mm	**Size**	215(L)*55(H)mm
Mother board		**Optical communication board**	
CPLD	EPM7064STC44-5	**Communication speed**	12Mbps
Hard disk	40 GB		
I/O connections	CPU, Motor controller & Optical communication boards. LAN, IDE, CAN×2, CCD camera, LED light and 4 motors	**Allowable angle for the robot**	±6°
		Allowable angle for the receiver in the manhole	±1°
Size	243(L)*90(W)mm	**Size**	95(W)*75(H)mm

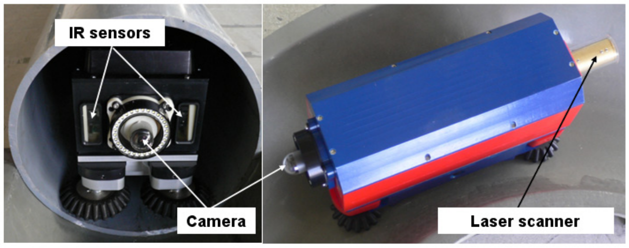
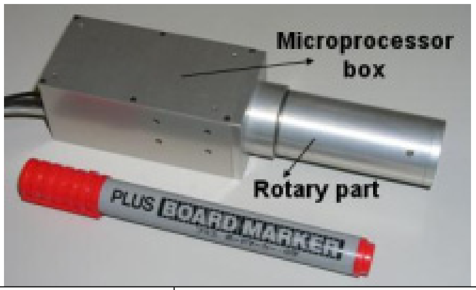


Fig. 14. First (right side) and second (left side) version of KANTARO. Kantaro's sensor system consists a camera, one laser scanner, a tilt sensor mounted on the mother board and two IR sensors.



Scanning directions	**360 degrees**
Scanning speed	**0-1800 (rpm)**
distance range	**70-190 (mm)**
Accuracy	**±1(mm)**
Beam radius	**0.5 (mm)**
Transmission method	**Full duplex serial transmission (2Mbps)**
Sampling speed	**More than 10 KHZ**
Measuring signal output	**Distance, Scanning angle**
Wight	**200 g**
Size	**37×48×166 (mm)**
Power	**±12V(0.5A) +5V(1A)**

Fig. 15. The newest laser scanner is capable to detect the navigational landmarks, independently with the main computer, as a sensor module.

manholes, inlets and pipe joints used for damage-navigation, independently, by using a powerful Microprocessor (SH-2) as well as measuring distance and scanning angle, linearized and filtering and modeling data. For realization of a 360 degrees infinitive rotation in laser scanner, we developed a small and special magnet coupling to supply power to rotary part and transmit the laser signal to the Microprocessor box.

IV. KANTARO AS A FULLY AUTONOMOUS SEWER INSPECTION SYSTEM

In this section, first, we describe how KANTARO can be employed as a fully autonomous robot for finding the pipe damages and fault detection. Second, we will show our approach to make a safe and robust system in point of view of sewer inspection companies as users. KANTARO is capable to detect the candidate faulty images (called feature-images) on-board, by using a fast and simple edge detection program running on its E.B. module. Feature-images may include three different types of image:

- Landmarks (manholes, pipe joints and inlets)
- Faulty images (Fig. 16-left)
- Non-faulty images (e.g. images including trashes).

When robot detects a feature-image, an autonomous control program will start to decrease the robot speed for saving enough images, up to 5 frames, from feature-image area. Saving the images, directly, is done by ADV202 image compression chip, installed in CPU board, to the hard disk without involving CPU in saving process. At this time, the laser scanner, that has been kept switch off during the normal pipe condition (no feature-image detected by on-board program), will start to extract the possibility of happened feature fault as a land mark. In case of detection of fault as a land mark, the type of landmark, only as a code, will be saved via CAN interface into the hard disk. These start and stop process of saving data from camera and switch on/off the laser scanner perform a longer inspection process where we consider the capacity of hard disk and energy consumption. In addition, the time, robot speed and encoder data from four DC motors are saved to the hard disk during whole inspection process. After the robot is retrieved, all data saved in the robot hard disk will transmit via the LAN interface to the other PC. In this PC, three different programs are applied to extract the real faulty images from the retrieval feature-images and calculate the position of happened fault. First, the feature-images are divided to the landmark images and the faulty-non faulty images by applying the laser scanner data and the time to the images. In the next step, a special fault detection patented algorithm extracts up to 60-70% of the faulty images from the faulty-non faulty images (Fig. 16-right)[14]. Last, the rough position of the faults will be calculated by using the encoder data, robot speed and time. This program has possibility to accept the map data of the sewer network (position of manhole, inlets and pipe joints) and fusion with laser scanner data to decrease the error of wheels slip and more accurate calculation of the happened fault position. After of all, the remain faulty images including the necessary specification will save as a result of inspection process.

Nine types of fault
crack
water infiltration
root invasion
pipe break
pipe gap
packing gap
mortar
an alien substance
landslide

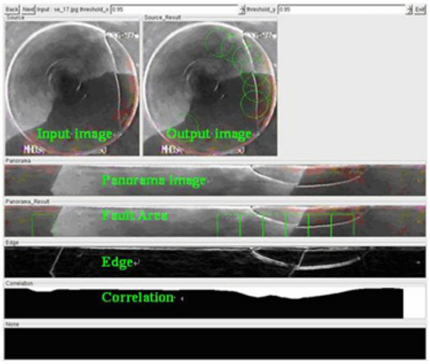


Fig. 16. Nine different types of fault, possibly happening in the sewer pipe (left side). An example of result of special fault detection patented algorithm applied on a faulty image including a crack (right side).

To make a practical, safe and robust system, we introduced a life-optic-untethered cable for KANTARO. With this cable that act as a tail for robot, operator can connect the robot to the control units located in out of the manhole via the fiber optic while the robot is driving into the pipe. In this case, operator can observe the condition of the pipe interior and also has possibility to control the robot and use the KANTARO as a semi-autonomous robot for pipe state assessment. Also this cable can be used as a life cable to pull out the robot in the case of stocking it inside of the pipe or power failure. The length of the cable is designed 50 meters as the same length as maximum distance of two manholes. In this approach, we could solve general skepticism about using fully autonomous systems without a possibility to interfere the robot control at any time. In addition, the operator can send the basic commands such as a move/stop the robot, turn on/off the light and save/not save data to the hard disk and so on via the optical underground wireless communication module.

V. EXPERIMENTAL RESULTS

We evaluated the performance of naSIR mechanism and our sewer inspection system by driving KANTARO in a sewer test field, in our RRI laboratory, which is made by PVC material with a diameter ranging from 200 to 300 mm. Our test field, including all kinds of pipe bends, small steps and also navigational landmarks such as manhole, inlets and pipe joints, can present as a sample of real world sewer network in Japan (Fig. 17). naSIR mechanism (KANTARO platform without upper box, showed in Fig. 4) is able to move in this sewer network up to 4 hours with one battery pack, charged in advance, without any control or stocking in the pipe bends and steps. Also KANTARO, as a whole system, has been successfully employed for autonomous damage navigation and fault detection up time about one hour (400 meters in advance). Figures 18_A and B indicate the motion of KANTARO prototype while passing a Y-junction and curve, respectively. In addition, we had several chance to drive and test KANTARO in real world sewage pipe network. Figure 18-C shows KANTARO while passing

Fig. 17. Our test field, including all kinds of pipe bends, small steps and also navigational landmarks such as manhole, inlets and pipe joints, can present as a sample of real world sewer network in Japan.

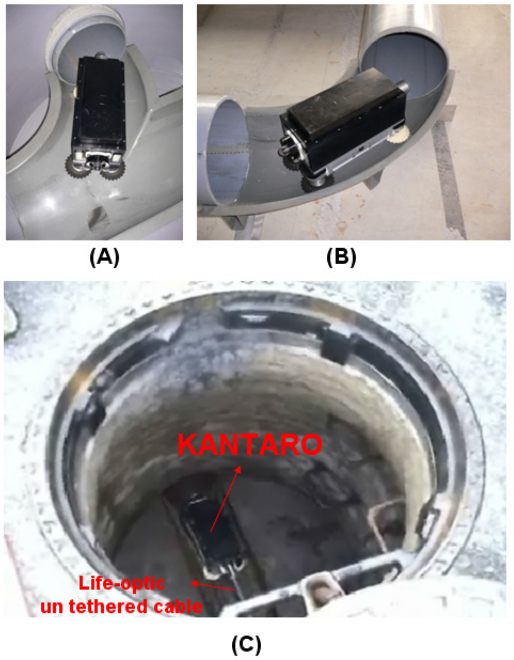


Fig. 18. (A) and (B) indicate the motion of KANTARO prototype while passing a Y-junction and curve. (C) shows KANTARO in real world sewage pipe network while passing a manhole.

a straight pipe with 250 millimeter in diameter. In this real test field experiment, KANTARO could successfully pass 80 meters pipe network, including 3 manholes and one junction, and perform all task mention in previous section.

VI. CONCLUSION

In this paper we proposed an innovative, fast and robust sewer inspection method by using a passive-active intelligent, fully autonomous, un-tethered robot,called "KANTARO", which fits to the pipes within a diameter range of 200-300 millimeters. KANTARO prototype robot, including a novel passive-active intelligent moving mechanism (naSIR mechanism), has a robust movement into the straight pipe and smooth and rapid motion while passes different kinds of pipe bends without need of any intelligence of the controller or sensor reading. In this approach KANTARO does not request any kind of sensor for its motion inside of the pipe. In addition, we developed a small and intelligent 2D laser scanner for detecting of the navigational landmarks such as manholes and pipe joints independently with main computer system and fusion with a fish eye camera, mounted on the KANTARO, used for assessing the pipe state and fault detection. Realization of KANTARO as a fully autonomous, reliable and robust pipe inspection robot has been achieved by designing an architecture based on intelligence at its modules and definition and implementation of a life-optic-untethered cable to make the inspection process easily and safely. To prove that KANTARO is able to use as a commercial product, We still have to perform further experiments in real world sewer pipe network with different in size and state pipe condition. Improving the offline fault detection software to get high accuracy is on the future work.

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