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Synopsis

"Aquarobot" is a robot that has been designed for underwater inspections in place of divers in port construction works. The Aquarobot has six legs similar to those of an insect, which are arranged in an axially symmetric manner. It is able to perform various kinds of inspection tasks while walking on a sea bed up to a depth of 50 m. A TV camera equipped with an ultrasonic range finder is attached at the tip of a manipulator of the robot for measuring the dimensions of an object on the CRT.

The robot is navigated with the aid of a long base line ultrasonic positioning system that is newly developed for the robot. The accuracy of the system is about 10 cm. The robot is able to make an accurate depth map of sea bed by using both the positioning system and a depth meter.

Its usefulness was confirmed through several field test. The test results were as follows: The walking speed on a rubble mound at a water depth of 50 m was 1.4 m/min., and the positioning accuracy was 1~35 cm. The depth measurement by the robot was as accurate as those by human divers.

Key Words: robot, underwater inspection, measurement of unevenness, actual test

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11. 歩行式水中調査ロボットの開発（第二報）

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要 旨

水中調査ロボット「アクアロボ」は港湾工事において潜水士に代わって水中調査作業を行うロボットである。アクアロボは軸対称に配置された昆虫型の六本の脚を用いて水深50mまでの海底上を歩行しながら種々の調査を行うことが可能である。マニピュレータの先端には超音波距離計を備えたTVカメラが取り付けられており，被写体の寸法を計測できるようになっている。また，歩行することによって足先の着地点の座標を読みとることで凸凹測定が可能である。数回の現地実験によってその実用性が確認されている。実験結果は以下の通りである。

水深50mでの捨石マウンド上での歩行速度は1.4m／minであり，位置測定精度は±21cm以下である。凸凹測定の測定誤差は潜水士が測定したときとほぼ同等である。

キーワード：ロボット，水中調査，凹凸測定，実海域実験

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1. Introduction

Port construction works are carried out in a widely diversified natural environment. And the scale of objects to be worked out is large and the working conditions are severe. Therefore, various kinds of machines have been used in port construction works. But the use of automated and robotic equipment is extremely difficult in this area, specially in the case of underwater works, where the work target cannot be easily recognized. Moreover, many adverse conditions exist underwater such as the necessity of waterproofing, influence of fluid resistance, problems of corrosion or pressure, poor visibility, restricted communication means, and thus automation and using robots are more difficult compared to construction works on land. For the above reason, robotization has been delayed in the construction area compared to the industrial production area where the introduction of industrial robots has advanced and made achievements. However, robot technology has recently advanced. The introduction of robots to areas previously considered difficult has become possible. The problem of labor shortage has become more serious. These two factors have contributed in placing a higher priority on of introducing robots even into construction areas. Also, in the port construction area, the importance of ocean development has increased and a more efficient utilization of space such as water front development is now required, and thus the necessity of automation and robotization in port construction works has considerably increased. Also, underwater works by divers, which is indispensable for underwater works, is extremely heavy and dangerous labor.

The necessity of automation and robotization is high from the viewpoint of freeing human beings from hard work and coping with the labor shortage.

In response to the situation, the Port and Harbor Research Institute has introduced researches on robots for various tasks associated with port construction works. One of the principal themes of R&D by PHRI is the "Aquarobot" — aquatic walking robot for underwater inspection — and we have already developed the third experimental robot. For the second experimental model — a waterproof type experimental model, we carried out field tests on four occasions and confirmed that the walking performance has reached a practical level.

The aquatic walking robot for underwater inspection is expected to be soon put to practical use, and this paper will mainly describe the third and fourth field tests conducted in Kamaishi Port using the underwater experimental model.

2. History of the Development of the Aquatic Walking Robot for Underwater Inspection

Port construction works and ocean civil engineering works inevitably require underwater works by divers. These can be classified into the underwater works performed for construction works by the contractor and the underwater works performed by the orderer for instructing, supervising and inspecting the works. However, the underwater works by divers had the following problems:

In 1985, about 3000 divers were engaged in underwater works in ports. The divers were advancing in years, however, and a shortage of divers was expected. At present, the number of divers engaged in port construction works has considerably decreased because of advanced age and the extremely hard, dirty, severe works conditions. In the port construction works in recent years, the water depth has greatly increased. In the case of Tsunami breakwater construction works in Kamaishi Port, a depth of 60 m has been recorded in the construction area.

According to the Ministry of Labor Ordinances, the allowable total time of underwater works by diver per day is 8 hours for a depth of 10m. But it decreases to 4 hours for 20 m and to 75 minutes for 50 m. Moreover, the number of divers experienced for great depths is extremely small at present.

Because of the decrease in the number of divers, the decreased quantity of light and the worsened conditions of marine phenomena, work efficiency is reduced as the scale of port works increases and the water depth in work area becomes greater. Because of the hazards involved in working in the ocean, underwater works using divers is naturally dangerous. The fatality rate among divers is much higher compared to the construction workers on land. The degree of danger is considered to further increase as the water depth at the working site becomes greater.

Another problems involves the accuracy of the data obtained by divers. The government and the port authority, who are responsible for implementing public projects, perform inspecting and supervising work based on data obtained by divers. In order to correctly make engineering judgements, it is much desired that objective data free of diver's subjectivity is obtained. For the above reasons, we decided to start the development of the aquatic robot for underwater inspection in order to secure the safety and efficiency of port construction works, to free human beings from dangerous work and the pains of repetitive work, and to enhance the accuracy and quality of port construction work.

Previous ocean robots can be classified into tethered type and non-tethered type. Research activities on non-tethered type have been increasing recently but this type is still in the research stage. The tethered type can be further divided into the hanging type, towing type, floating type and moving on sea bed type. In the inspection work performed in the port construction work, the aquatic robot for underwater inspection must have two functions; it must be both mobile and able to maintain a sedentary position on the sea bed. Among the previous types of ocean robots, the above requirements are fulfilled by hanging type, floating type and moving on sea bed type. Among them, the moving on sea bed type is best suited for underwater inspection to be used by the District Bureau of Port Construction. The moving on sea bed type can be further classified into wheel type, crawler type, Archimedes' screw type and walking type. The wheel type has a simple structure and a high running speed (this type is widely used for on-land vehicles) but, for use on the sea bed, its adaptability to irregular terrain is small and its direction cannot be easily changed. The crawler type has a good adaptability to irregular terrain and high stability but considerably agitates bottom materials so that the visibility of underwater TV is disturbed during operation. Also, its structure is complicated and it is very heavy. The Archimedes' screw type has a simple structure but as this type was originally developed for operation on soft ground or ice where the friction is small, it is not suited to running on base rock where the friction is large. On the other hand, the walking type has a high adaptability to the irregular surface compared to its size. Its area of contact to ground can be reduced and thus it can walk without making the water muddy. Moreover, its moving direction can be easily changed. In addition, the main body can be always held horizontally. This is suited to the use of various inspection equipment. For these reasons, the walking type is the most suited for underwater inspection. Thus, the walking robot was selected as the type of aquatic robot for underwater inspection to be developed by the Port and Harbor

Research Institute. The research and development work was then started for the experimental model called "Aquarobot". The Aquarobot has two functions suited to the inspecting work accompanied with port construction. One of them is the function to measure the unevenness of rubble mound from the movement of the legs during walking. The other is the function to observe and measure the underwater structures by TV camera. The Aquarobot is set on the sea bed so that the picture is stable and measurements can even be taken from on the CRT.

3. The Architecture of Walking Type Robot for Underwater Inspection

3.1 Conceptual Design

There are various types of walking robots so we performed a conceptual design for selecting the optimum method.

The number of legs is one of the most important factors for walking robots. The robots already researched have one, two, three, four, six or eight legs. One-legged robots are used for research of dynamic control. They are not for practical use. Two-legged and three-legged types require dynamic control and their stability is problematic for practical use. Static walking robot is suited in view of the practicality of walking in water, and the aquatic robots need more than four legs. For four-legged robots, dynamic control is not needed but its center of gravity location must be always monitored, and its walking speed is low since only one leg is raised at a time. Six-legged and eight-legged robots are able to walk statically without monitoring the position of the center of gravity. In this case, control is simpler for six legs and also weight can be reduced. Also, the legs are less interfered with so that the operating range of legs can be made larger. In the alternate foot transfer pattern, eight-legged robots have a larger number of contacts to ground and have better stability; but it is possible for six-legged robots to walk with four legs or five legs contacted to ground if the software control method is adopted. So the use of eight legs just for increasing the number of legs contacted to ground is not required. The static walking speed and stability allowance rapidly increase up to six legs but hardly change when eight legs are used. Based on the above, the six-legged walking robot is considered to be the most suitable for practical use.

In a six-legged robot, there are two arrangements of legs. One is the plane-symmetrical type having three legs at each side of the body. And the other is the axis-symmetrical type having legs at intervals of 60°. The axis-symmetrical type can walk in any direction without changing the directions of the body and can easily turn the body within its own space; therefore, it is suitable for the aquatic robot for underwater inspection required to move quickly in response to the topography of the sea bed.

The walking robot can be classified by the shape of leg; the Mammalian type in which the leg is always directed in a vertical direction; and the insect type in which the leg is extended out from the body and the operating angle of the joint of leg is large. The insect type provides a larger operating distance of leg compared to the size of main body, therefore, if the size is the same, the walkable surface with irregular topography is larger compared to the Mammalian type. Because of this, the insect type is more suitable for putting on a small supervising ship.

The walking robot can also be classified by control methods: mechanical control method and software control method. The mechanical control method induces the mechanical walking motion of leg by using a link mechanism etc. In the software control method, each leg articulation is mechanically independent, and the walking motion is made by cooperative control by a computer program. In the mechanical control method, the degree of freedom of motion becomes smaller and the load to controlling computer is reduced, so that higher walking speed can be realized but, on the other hand, the degree of freedom of walking is small and walking on irregular surface becomes difficult. Also, the mutual positions of legs in a set cannot be changed, so that walking by selectively touching the ground to avoid a dangerous area is not possible. In the software control method, the motion is not limited within the operating distance of legs and thus each leg can be moved independently from others so that walking by selectively touching ground is possible; but the amount of calculations required for control is extremely large and the program becomes very complicated; thus the load to control computer increases and the walking speed tends to slow down. However, a compact, high-speed, large-capacity computer can be utilized as a result of the progress in computer technology in recent years, thus a practical processing speed can be now obtained. Also, the control is performed by always calculating the leg positions in order to adapt to unevenness in topography in this method, and thus it has another advantage of surveying the unevenness in topography from the locus of leg touching points to ground. For the above reasons, we decided to adapt the software control method.

As power sources, hydraulic type and motor-operated type can be considered. The hydraulic type has a big output but its weight including power unit becomes heavy, hence we decided to use the motor-operated type suited to computer control.

Generally, many walking robots are equipped with actuators on the bodies, but the Aquarobot has the actuators at the leg portions for reducing driving torque. Many industrial robots have the actuators centered at the base for increasing the loads capacity. However, the walking robot supports the main body with the tip of the foot as fulcrum. Since the moment at the joints can be reduced, heavy parts like motors are installed in the leg portion.

By adopting this structure, the various types of inspection equipment can be placed in the main body and this method has another advantage in that waterproofing is easy. By the conceptual design, it is decided that the type of the aquatic robot for underwater inspection to be developed by the Port and Harbor Research Institute should be a motor-operated, axis-symmetrical, six-legged, insect type software-controlled walking robot. As the figure of main dimensions of the Aquarobot was reported in reference (22), we will omit it here.

3.2 Hardware

The Aquarobot comprises a main body of robot and a controller. Main material is anti-corrosive aluminum. As the controlling computer, an ordinary 16-bit micro-computer was used. Main body of robot and the controller installed on the mother ship are connected with a cable.

For the leg structure, a semi-direct drive method is adopted, in which a motor is provided inside the leg and each articulation is driven by a motor only through a reduction gear for dispersion of weight and easy waterproofing. Each leg has three articulations because three degree of freedom are required for moving the tip of the leg to any position.

The rotation axis of the first articulation that is nearest to the body is vertical, and the rotation axes of second and third articulations are horizontal. The Aquarobot has 18 motors in total for six legs.

A foot portion is attached with a ball joint to move fitting to an inclination of the ground. A touch sensor is installed at the tip of the leg for detecting contact with ground. This permits its adaptation to the irregular surface of ground.

The motors are controlled using the servo driver method. The motor with the driver can be controlled accurately by controlling the pulse generation from a control computer. According to this method, encoder signals for feeding back leg position information are not required to be processed by the control computer, so that the walking speed can be increased. The control computer is connected to the servo driver through parallel input/output ports. The torque that is necessary for each articulation is estimated regarding the frictional force of the sole of the foot. This method is shown in **Fig. 1** and **Fig. 2**. This is the design method developed by the Port and Harbor Research Institute.

When a walking robot is standing, a moment $M = aF$ acts to the articulation A by the force F acting to the sole of foot as shown in **Fig. 1**. When M is smaller than the maximum output (servo rigidity) of actuator, the robot can keep on standing. If the weight of robot increases, F becomes larger, and M exceeds the maximum output (servo rigidity), then the articulation is unable to maintain the angle and the tip of the foot tends to slip. When the tip of the foot is just about to slip, a frictional force Fs occurs at the sole of the foot in the opposite direction of slip as shown in **Fig. 2**, and the moment occurred at the articulation A decreases to $M = aF - bFs$. On ice, where the coefficient of friction is extremely small, a human being is unable to stand while spreading his legs, but this is possible on an ordinary ground surface by the same reason.

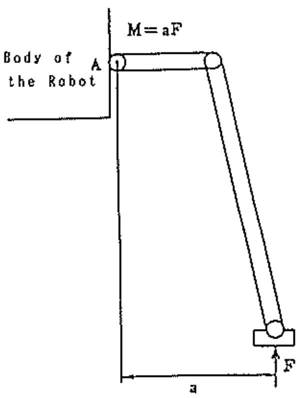

Fig. 1 Without Frictional Force at the Sole of Foot

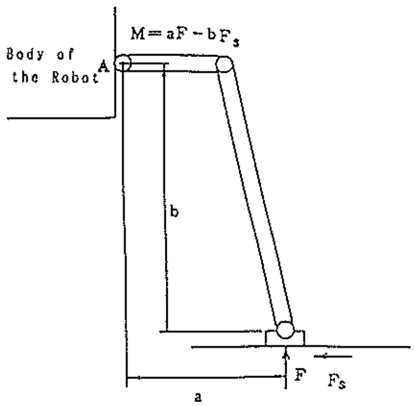

Fig. 2 With Frictional Force at the Sole of Foot

3.3 Software

Aquarobot control program consists of two parts, the robot operating program and walking algorithm program. Architecture of program is shown in **Fig. 3**. By using such a class structure, the efficiency of program development increases and the maintenance becomes easier. BASIC (compiler) language and assembly language are used to develop the program.

(1) Robot operating program

This program receives the coordinate values (PTP) of moving target points of the tip of leg from the walking algorithm program. And the program prepares in real time mode the detailed operation commands (CP) from said information and controls the

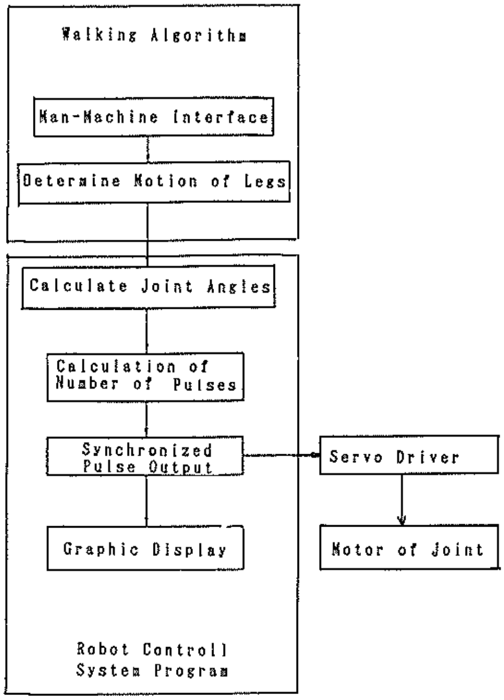

Fig. 3 Architecture of the Program

motors. This method was adopted because it is necessary to change the motion of leg depending on the unevenness in topography during the walking of Aquarobot, so that the sensor information must be fed back for each step and the acting path cannot be determined in advance being different from an industrial robot. This program contains a robot language as the interface with the walking algorithm program.

(a) Robot language

The leg of Aquarobot is of articulated type, the coordinate system for control is the polar coordinates with the axis of articulation as the center. But the coordinate system required for the operation of leg during walking motion is cartesian coordinates. So coordinate transformation becomes necessary. The robot language gives the leg operation with the cartesian coordinates by software. This coordinate transformation was achieved by developing the linear interpolation and pulse synchronous output program.

(b) Linear Interpolation

When making a walking motion, the tip of leg must move along a straight line connected from the present position of leg tip to the moving target point.

It is necessary to consider numerous interpolation points on the straight line connected between the two points, and the tip of leg must pass each point sequentially. The angles of three articulations when the tip of each leg is at the position of each point are determined by calculations. Three articulations are synchronized and rotated in such a manner that the calculated angle occurs sequentially. And the tip of leg moves on the straight line connected between two points. This method uses straight line interpolation by absolute coordinates. The number of interpolation points in this program is reduced to the several points which are necessary to effect walking.

(c) Synchronization of Motor Rotation

When the tips of legs do not operate in synchronization during walking motion, each leg will react with the others, thereby increasing the load of motor and prohibiting smooth walking. If this synchronization is performed correctly, the number of interpolation points can be reduced. When the tips of six legs move simultaneously from interpolation points to next points, 18 motors in total must rotate and thus 18 output pulses are calculated. The numbers of these pulses are generally different from each other. Therefore, for synchronizing the tips of legs, the pulses must be output in synchronization with the motor controller at the speed proportional to the respective pulses. The pulse output start time and end time coincide at all the articulations, and the tips of legs move by synchronization. This pulse synchronization output program directly affects the walking speed of Aquarobot, and thus a special algorithm was invented and developed by using assembler language.

(d) Graphic Display and Simulator Functions

This program shows graphically the posture of Aquarobot on CRT at every step of the motion of leg in real time mode. This is a function required for operating the Aquarobot in sea water where it cannot be seen directly. It checks whether any command exceeding the motion space of leg mechanism is being sent or not. Because of this, it is utilized for debugging the walking algorithm program.

(2) Walking Algorithm Program

Main task of this program is to interpret the command from operator and to prepare the coordinate values (PTP) of the operation target points at the tip of leg required for executing the command.

(a) Walking algorithm

According to the basic walking algorithm, every second leg (three legs in total out of six legs) is considered as 1 set. Legs in one of the sets support the body and the other legs of other sets are raised in the air thereby using the alternate foot transfer pattern. This alternate foot transfer pattern is the walking pattern. This alternate foot transfer pattern is the walking pattern of "six-leg used with three-leg supporting." In addition to the above, walking with other various patterns is possible by changing the combinations of the numbers of legs used and the numbers of legs touched, such as six-leg used with three-leg touch, six-leg used with five-leg supporting, five-leg used with three-leg supporting, five-leg used with four-leg supporting and four-leg used with three-leg supporting. This is possible because this robot has six legs while the minimum number of legs required for static walking is four. Since there is a redundancy in the number legs, it is possible to use a leg which is not used during walking as manipulator or to continue the walking if one or two legs become damaged. As shown in **Fig. 4**, the basic operation of each leg is the repetition of walking operation (rectangular operation) of (1) raise the tip of foot, (2) put it forward, (3) lower it to touch the ground, and (4) move backward. The tip of foot always moves straight forward in horizontal or vertical direction on the rectangular sides. Because of this, the main body will not be swung or inclined. The walking algorithm is shown by a flowchart in **Fig. 5**. Information from touch sensor, inclination sensor and compass is automatically judged in real time mode and the posture is automatically corrected, so that it is able to respond to the deformation of walking surface and slipping of foot without accumulation of operation error. At the time of guided walk, the present position of Aquarobot is measured by an underwater position measurement system every one to two steps, and the direction and distance to the walking target position is renewed.

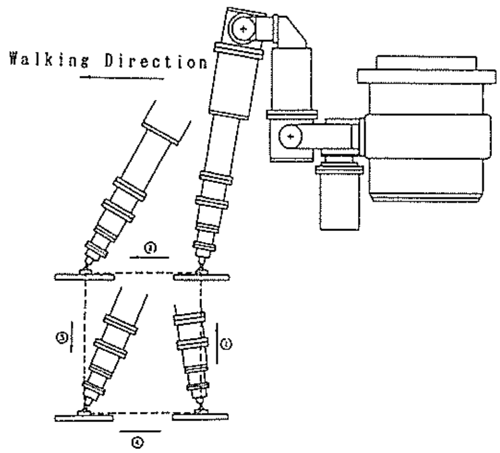

Fig. 4 Basic Operation of Each Leg

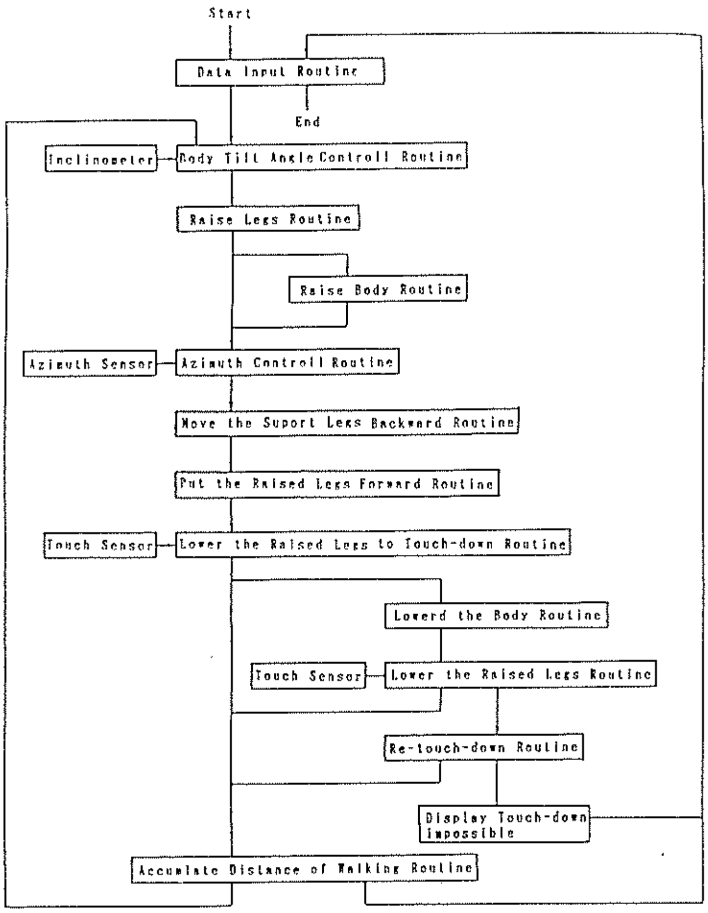

Fig. 5 Flowchart of the Walking Algorithm

(b) Man-machine Interface

This program uses a conversational system. The operator is required only to select functions from menu and to respond to questions from program. After the input, the tip coordinate value of leg required for automatic operation is sequentially calculated and the operation is performed instantly. In the case of no guidance, walking direction (any of absolute azimuth, coordinate system of walking area and robot coordinate system can be selected) and walking distance are given. With the guidance provided, XY coordinates of walking target point are given. Also, a rotation angle is input in the case of rotation in-situ. As a further automated function, width of measurement and the coordinates of apex of the area, where unevenness measurement is required, are given, traverse lines are automatically generated and the walking can be made sequentially along the traverse lines. This function is called "plane scanning walking function." Parameters such as the coordinates of apex, scanning width, scanning direction, scanning start point, etc. can be freely changed and verified by graphic display. **Figure 6** shows an example of parameter change for plane scanning walking functions.

Length of steps and foot-raising height during walk can be freely set within the range permitted by the mechanism, and also the optimum value can be automatically estimated.

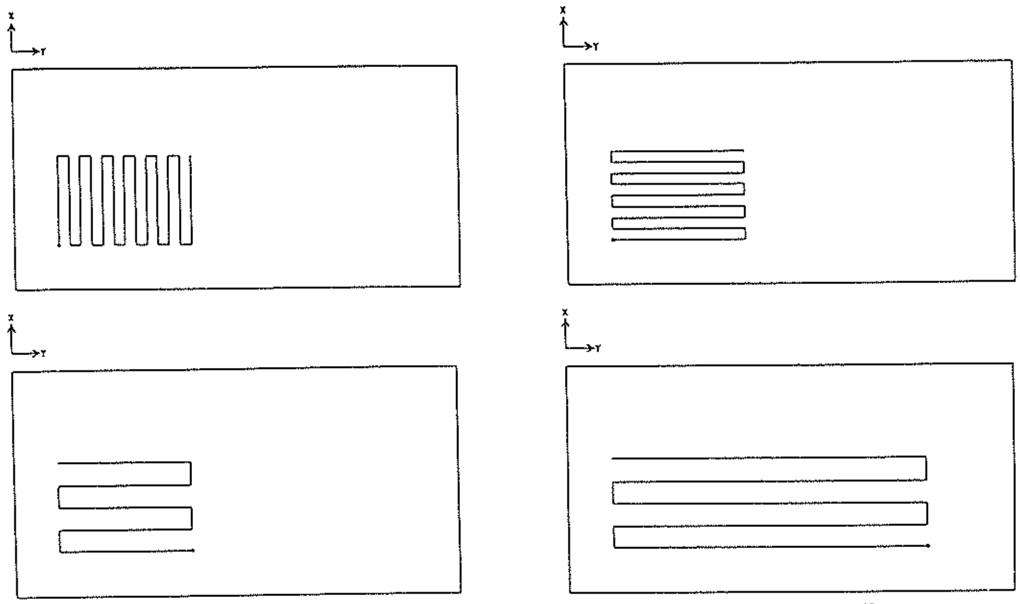

Fig. 6 An Example of Patrameter Change for Plane Scanning Walk

(c) Unevenness measuring function

Schematic drawing of walking state of Aquarobot is shown in **Fig. 7**. Even on irregular terrain, the body is always held horizontally or to an arbitrary angle. Leg position is always known by the controlling computer, and thus unevenness of ground surface, on which the Aquarobot walked, can be known by plotting the locus of the tip of leg. As stated above, the special features of Aquarobot are such that not only the moving function but also the unevenness measuring function for the ground on which the Aquarobot walked are known from the walking movement.

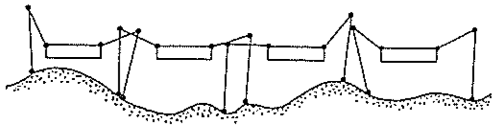

Fig. 7 Schematic Drawing of Walking State

(d) Landing Point Changing Function

If the touch sensor does not turn on after fully lowering an off-floor leg during walking, then this landing point is judged to be touch impossible; and it will be touched down to another point automatically by the landing point changing function. Because of this, the leg will not be inserted in a hole. If the touch sensor does not turn on after performing the landing position changing function operations several times, then touch-down impossible is judged, and "touch impossible" is displayed on the screen and menu screen occurs.

(e) Joint operation range extension function

For the purpose of walking on irregular terrain, it is generally required to perform the walking operation for moving the tip of foot on the sides of a rectangle as shown in **Fig. 4**. However, the moving range of the tip of foot of the articulation type leg is surrounded by a spherical surface so that numerous rectangles are contained within the moving range. Only one of them is selected before walking. However, the selection of rectangle becomes problematic in this method. The reason is as follows: if the length of step is increased for increasing the walking speed, then the foot-raising height decreases, so that the walkable unevenness decreases. And it the foot-raising height is increased in order to increase the walkable unevenness, then the length of step decreases so that the walking speed is delayed. In this method, the use of whole zone of the articulation operation range is not possible. The articulation operation range extension function does not determine the rectangle, which performs the walking operation before walking, and selects the optimum rectangle within articulation operation range for each step with respect to the topography. This algorithm is so arranged that the maximum range operable next can be calculated from the foot position at each touch-down.

(f) Main body tilt angle control function

Generally the walking robot walks while maintaining its body horizontally. It is necessary to stabilize the body horizontally after the body is tilted by a slip of the tip of foot or collapse of ground. The body tilt angle control function is able to freely change the body tilt angle without changing the relative positional relation between the center of body and the tip of foot of touch-down leg; there is no slip of foot and movement of the center of gravity due to the change in tilt. There is no error even if the tilt correction is large because the strict solutions of the direction and size of the tilt of body are determined from the information from tilt sensor and the articulation type leg having three degrees of freedom is software-controlled.

(g) Main body tilt walking function

The main body tilt walking function is able to hold the main body not only horizontally but also at an arbitrary angle during walking. On a slope, walking with the body held horizontally is sometimes not possible since the foot touches the floor. But the walking can be made possible by tilting the body in the direction of the slope. In this case, if the legs of robot are controlled in the coordinate system fixed to the main body, a problem due to the movement of the center of gravity is created. And this must be avoided by reducing the walking ability such as limiting the movable range. In this case, the coordinate conversion must be newly performed for the walking robot controlled by the rectangular coordinate mechanism fixed to the body so that the control becomes difficult. However, the Aquarobot, adopting the software control method, originally performs the coordinate conversion, so that it has the advantage of providing only a slight change in complication of control.

(h) Walking parameters estimating function

Parameters required for walking such as length of step, height of foot-raising, height of body and tilt of body are normally specified by the operator before walking and are constant during walking. However, if the state of unevenness changes as in the case of moving from a sloped surface to horizontal plane, efficient walking without wasteful movement of feet can be performed as long as the walking parameters are changed in response to the state of unevenness. The walking parameters estimating function judges the degree of unevenness from the positional relation of the tip of foot by using the unevenness measuring function and automatically selects the values of the optimum walking parameters against topography by using the inference algorithm. Also, this function contains the judgment of whether leg operation range extension function or body tilt walking function is to be used or not.

4. Construction of Experimental model

4.1 On-land Experimental model

(1) General

In fiscal 1983, we made an apparatus for articulation tests having one joint with the structure as described in Par. 3.2. Based on test results of this apparatus, we developed an on-land experimental model, No. 1 model of Aquarobot, in fiscal 1984. The on-land experimental model was made to verify the effectiveness of design conception explained in Chapter 3 and for the development of walking algorithm. Since this model is for on-land walking tests, waterproof design was not made. A joint structure that can be easily waterproofed was adopted. Since no buoyancy acts on land, the leg length of one-half of underwater specifications was made in order to support the deadweight.

In fiscal 1985, several improvements were made including the addition of sensors for making possible the walking on irregular terrain. The on-land experimental model consists of the robot body and controller. Appearance of the main body of robot after improvement is shown in **Photo. 1**, the principal dimension in **Fig. 8** and specifications in **Table 1**. Since the joint angle detecting encoder is of incremental type, the initial position sets on the support before operation. No brake is equipped for the articulation.

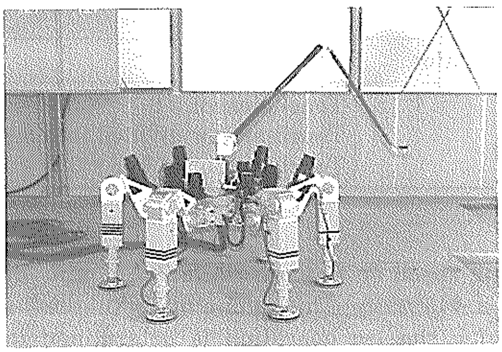

Photo. 1 Appearance of the Aquarobo 1

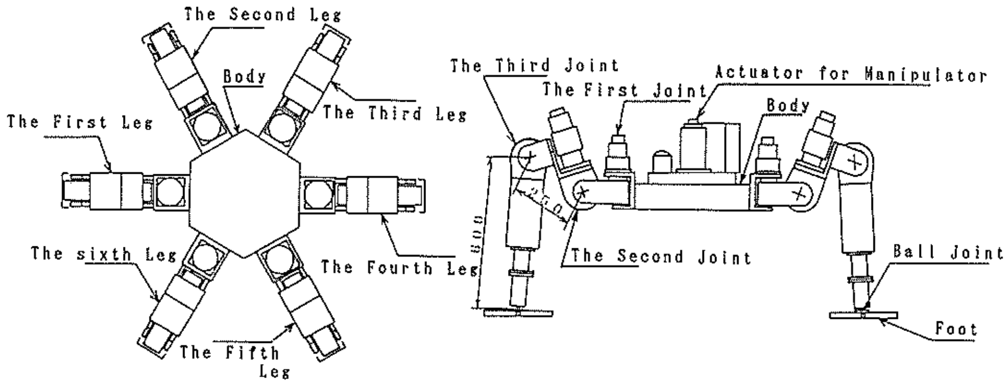

Fig. 8 Principal Dimensional Shape of the Aquarobot 1

Table 1 Main Specifications of Aquarobot 1

Form	Motor-operated Axis-symmetric, Six-legged insect type, Software-controlled
Driving System	Semi-Direct Drive by DC Servo Motor
Control System	Software Control by Personal Computer
Walking Ability	±17.5 cm
Main Material	Anti-corrosive Aluminum
Weight	280 kgf
Dimension	Body Hexagon (side length 25 cm)
Number of Joints	3 Joints for each leg, 1 joint for the Manipulator
Actuator	DC Motor
Output Power of Actuator for Legs	80W for 1st Joints, 120W for 2nd and 3rd Joints
Output Power of Actuator for the Manipulator	80W
Rotation of the Manipulator	±180 degree
Sensors	Touch-sensor × 6 Touch-sensor divided into 8 sections at sole × 6 Touch-sensor at Toe × 6

(2) Performance

Maximum walking speed on flat terrain is 7.5 m/min. during straight walking, while rotating speed is 445°/min. This is one of the highest speeds in the world for walking robots in which the leg operation is determined in real time mode. The walking test on the irregular terrain was carried out on a rubble mound constructed on land. The rubble mound used for the test had a horizontal surface (3 m wide and 6 m long) and a sloped surface with gradient of one-fourth (14.03°). This mound was constructed with real crushed stones by divers who were actually engaged in leveling works in the water. The leveling accuracy of the mound was set to 5 cm, the same as the actual figure in final leveling. And in rough leveling it was set to 15 cm which was one-half of the actual figure, because the leg length of on-land experimental model was one-half of that of the practical-use robot. In the case of walking on a horizontal surface, the walking was possible without problem while holding the body horizontal. The walking speed was 1.7 m/min. maximum on the final leveling surface. At first walking on the slope was not possible but was made possible by additional functions derived by improving the program. Walking on the sloped surface became possible by using the range extension function of the articulation operation, but it was necessary to support the foot portion for preventing rubble contact with the foot. Therefore by using the body angle inclination walking function, it was able to walk perfectly on the sloped surface. The time which was required for climbing the inclined surface was reduced to about one-third by the walking parameter estimating function. As a result of the walking test, it was substantiated that the Aquarobot can autonomously walk on the irregular terrain in advance using the software control by selecting the optimum walking parameters. Particularly, the robot was able to climb and descend the uneven surface using its own judgement. This cleared another hurdle towards practical use.

The experimental model can walk while supporting one person with a weight of about 70 kg. No walking robot of the same size as the Aquarobot can carry a man. The walking tests confirmed that the design approach considering the friction force on the sole of foot is effective.

4.2 Waterproof Type Experimental Model

(1) General

A leg waterproof-designed apparatus was manufactured in fiscal 1985 for trial use. Based on the experimental results of this leg apparatus of waterproof structure, a waterproof type experimental model was manufactured as Aquarobot No. 2 in fiscal 1986. This was produced as a prototype; the specifications were the same as those of the practical-use model that we scheduled to manufacture in the future. The robot can walk at a depth of 50m underwater, and it can walk on the surface of which roughness is ±35 cm. The waterproof type experimental model consists of the main body of robot and its controller. Signal transmission was performed by an optical communication method, and the body of robot was connected to the controller by photo-electric power compound type optical fiber cable. Accordingly, a photo-electric converter was built in the main body and controller respectively. The leg had the structure equal to the on-land experimental model. It was waterproofed by double seal. Waterproof magnetic proximity switches were adopted in the touch sensor. Using this, the influence of water pressure was canceled, and the sensors were improved to operate under the same acting force regardless of water depth. The control speed of the program was made sufficiently high so that the stroke of the touch sensor was made smaller compared with the on-land experimental model. The new smaller type of servo driver was adopted and overall arrangement was re-examined. Thus, the controller was made smaller by about one-third (volumetric ratio) of the drive panel for on-land experimental model. Nevertheless a photo-electric converter and interface box were built in it. Because of this, it was more easily loaded on a ship. Articulation output power was increased in fiscal 1988. Improvements were made such as change of the foot shape and addition of directly attached floats in 1989. **Photo. 2** shows the waterproof type experimental model after the improvements were made; principal dimensions and sensor position are shown in **Fig. 9**, and specifications in **Table 2**. Appearance of controller after improvement is shown in **Photo. 3** with the specifications in **Table 3**.

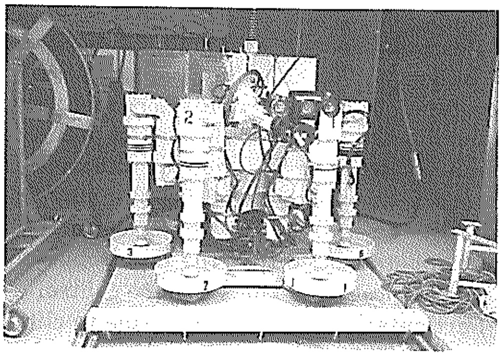

Photo. 2 Appearance of the Aquarobo 2

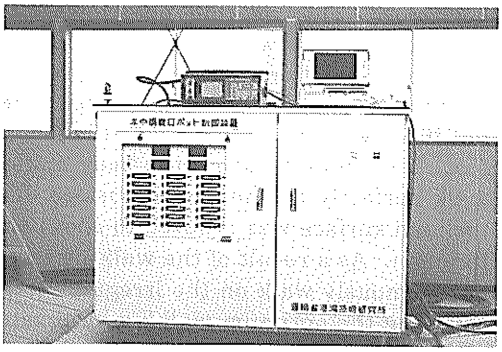

Photo. 3 Appearance of the Controller

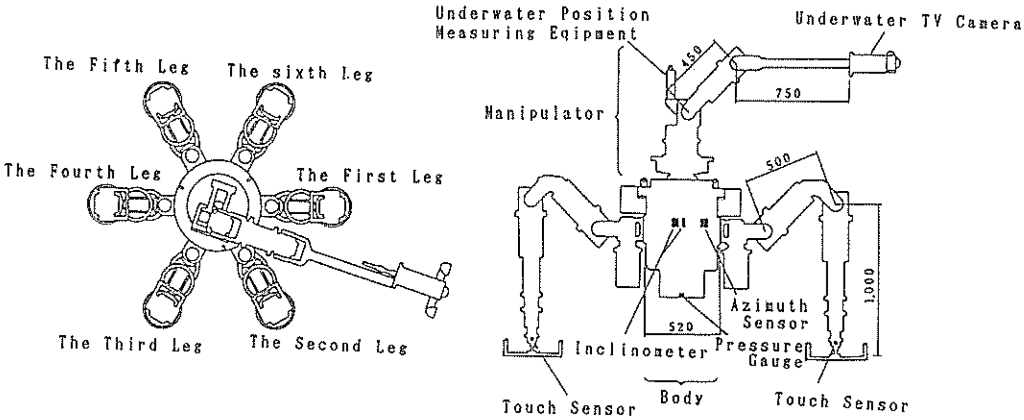

Fig. 9 Principal Dimensional Shape of the Aquarobot 2

(2) Manipulator

Underwater TV camera manipulator was installed on the body of robot.

Manipulator for underwater TV camera required a sufficient handling load for holding the underwater TV camera. Because of this, the weight of manipulator itself is desired to be concentrated at the base portion. In order to increase the photographic range of the underwater TV camera, it was necessary to make the movable range of manipulator as large as possible. Link structure was able to concentrate the actuators at the base, but the movable range was limited. And it was difficult to make a waterproof structure. Because of this, we adopted the articulation direct drive method

Table 2 Main Specifications of Aquarobot 2

Form	Motor-operated Axis-symmetric, Six-legged insect type, Software-controlled
Drive system	Semi-direct Drive by DC Servo Motor
Control system	Software Control by Personal Computer
Walking Ability	±35 cm
Walking Depth	-50 m
Main Material	Anti-corrosive Aluminum
Weight	857 kgf in the air, 430 kgf in the water
Dimensions	Body hexagon (side length 50 cm) Height 77 cm Leg 50 cm (thigh), 100 cm (shin) Foot 45 cm (Diameter), 8.5 cm (Thickness)
Number of Joints	3 Joints for each legs 3 Joints for the Manipulator
Actutator	DC Motor
Output Power of Actuators for Legs	120W for each 1st Joints 250W for each 2nd and 3rd Joints
Output Power of Actuators for the Manipulator	80W for each Joint
Range of the Manipulator	1st Joint ±180 degree 2nd Joint −40~+50 degree 3rd Joint ±90 degree
Sensors	Touch-senor × 6 Inclinometer × 2 Azimuth Sensor × 1 Pressure Gauge × 1
Floater	59 kgf × 1 180 kgf × 1 19 kgf × 6

for the manipulator, the same as for the leg. For the first articulation, a donut shape having a center hole for inserting cables and inner gears was adopted. This was necessary because the robot body was connected to the controller by tethered cables so that interference with cable during manipulator rotation had to be prevented. Construction of the second and third articulation was almost the same as that of waterproof leg. Actuators for first and second articulations were arranged at the base of manipulator for increasing the handling load.

In consequence, the weight of manipulator in the air as single unit was about 70 kgf and handleable weight was set to 6 kgf.

Table 3. Main Specifications of Controller

Dimension	1,600(W), 1,230(H), 800(D)
Weight	250 kgf
Servo Driver	HS-350-6 × 21
Display	Current of Motor × 21 Inclination × 2 Azimuth × 1 Depth × 1 Finish Signal of Servo system × 21
Computer	16 bits Personal Computer CPU Intel 80286 with 80287
Optical-electronic Convert System	TV signal × 1 Encoder signal × 5 Sensor signal × 1 Spare
Length of Cable	100m

(3) Cable winding equipment

For the waterproof type experimental model, we adopted compound cable containing multi-core optical fiber as tethered cable. We manufactured a reel type cable winding equipment capable of winding the optical fibers without twisting the cable by optical accumulator. The cable winding equipment is shown in **Photo. 4** and the specifications in **Table 4.**

(4) Walking Performances

In the walking experiments on a plane in a test pool, the maximum walking speed was about 1.8 m/min. before improvement and 6.5 m/min. after increasing the joint output for improvement.

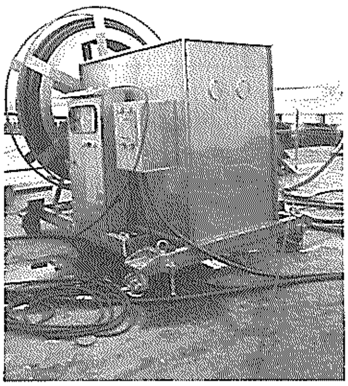

Photo. 4 Appearance of the Cable Winder

Table 4. Main Specifications of Cable Winder

Capacity	100 m (42 mm Diameter)
Winding Force	300 kgf
Winding Speed	2.5~10 m/min. variable
Dimension of Reel	1,3000 mm (diameter), 300 mm (Width)
Accumlator	9 optical fibers, 30 rotations
Slip Ring	70 points
Power Supply	AC 100V, 50~60Hz
Cable Composition	Compound cable (optical fibers and metal cable) (Metal) 0.75 mm² × 22 pairs for Actuator Powers 5.5 mm² × 1 pairs for AC 100V 0.75 mm² × 9 lines for Video Camera Control 0.4 mm² × 4 lines for reserve (Optical Fiber) GI 50/125 × 8 Length of the Cable 100 m Diameter of the Cable 41 mm Weight of Specific Length 1,660 gf/m (in the air), 370 gf/m (in the water) Specific Gravity 1.28 Strength 1,500 kf Minimum Bending Radius 40 cm

4.3 Lightweight Waterproof Type Experimental Model

(1) Outline

In order to develop the technology for making the robot lightweight and compact, we manufactured lightweight waterproof type structural legs on a trial basis by improving the articulation structure in fiscal 1986. Based on this achievement, we produced a lightweight waterproof type experimental model as No. 3 Aquarobot from fiscal 1986 to 1987. For this machine, the arrangement of actuator and reduction gear was reexamined. And articulations were made compact and lightweight and the leg was made slender. No manipulator was adopted and a TV camera was built-in to the main body. Also, the main body was used as a container for direct photo-electric converter. The controller was the same used in the waterproof type experimental model. The main body of lightweight waterproof type model is shown in **Photo. 5**, the principal dimensions and shape in **Fig. 10** and specifications in **Table 5**. The weight was considerably reduced while the length of leg remained the same as that of the waterproof experimental model. Purpose of the lightweight was to simplify the supporting system such as crane and to facilitate the improvement of walking performance by decreasing the inertial mass and fluid resistance.

(2) Lightweight techniques

In order to facilitate the creation of a lightweight and compact structure, data of

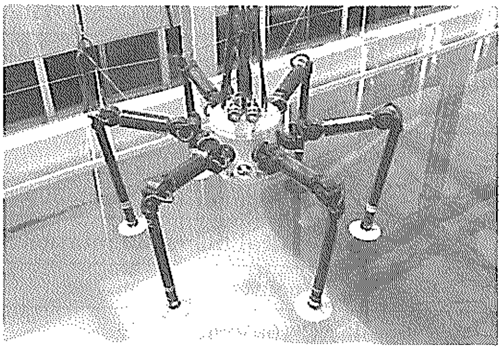

Photo. 5 Appearance of the Aquarobo 3

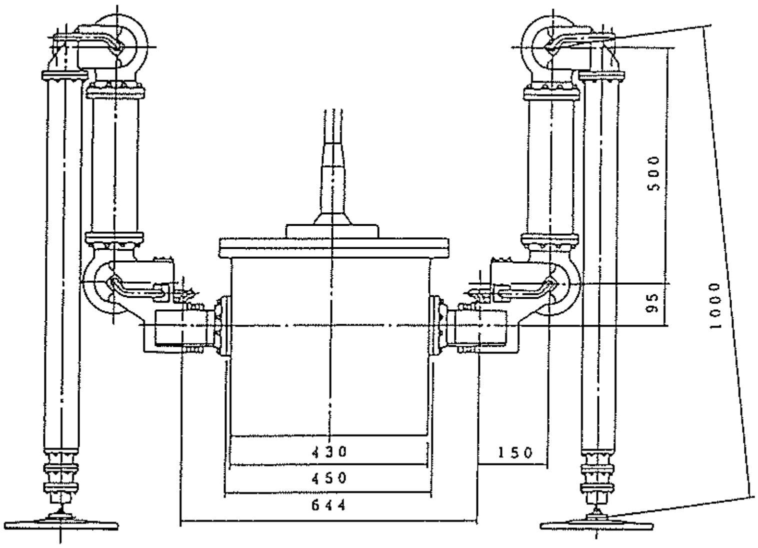

Fig. 10 Principal Dimensional Shape of the Aquarobot 3

the waterproof experimental model were used in designing the lightweight waterproof experimental model. The lightweight waterproof experimental model had the following characteristics:

Articulation portion which was previously made of many parts of simple shapes was arranged with a small number of parts with complicated shapes matched to the internal structure, by which the dead space at the joint portion and water proof portion was reduced. Up to now the actuator made of a motor and a reduction gear had been fashioned in one united body and placed in the leg, but this time the motor and speed reducer were separately built in the articulation structure so that the leg became more slender.

Actuator for first articulations was built in the main body and the actuators for both the second and third articulations were arranged in the femoral region, by which the number of waterproof blocks was reduced and the structure was made simpler. At the same time, it was possible to greatly reduce the number of cables, through-hole metal parts and waterproof connectors between electric circuits of the actuator and the inner part of the main body.

Table 5. Main Specifications of the Aquarobot 3

Form	Motor-operated Axis-symmetric, Six-legged insect type, software-controlled
Driving System	Semi-direct Drive by DC Servo Motor
Control System	Software Control by Personal Computer
Walking Ability	±35 cm
Walking Depth	-50 m
Main Material	Anti-corrosive Aluminmum
Weight	300 kgf (in the air), 150 kgf (in the water)
Dimensions	Body 43 cm (Diameter), 45 cm (Height) Leg 50 cm (thigh), 100 cm (shin) Foot 25 cm (Diameter)
Number of Joints	3 Joints for each legs
Actuator	DC Motor
Output Power of Actuators for Legs	80W
Sensors	Touch-sensor × 6 Inclinometer × 2 Azimuth Sensor × 1 Pressure Gauge × 1

When walking with the body in a horizontal position, a large output torque of the first articulation was not required so that a bevel gear was not used for the first articulation in the conventional method. However, a large first articulation output torque was required for walking with the main body inclined for increasing the climbing capacity. For the lightweight waterproof type experimental model, the first articulations had the same construction as the other articulations. Therefore the first articulation was raised up to the same torque as those of the other articulations. By doing this, the climbing capacity was increased. And the maintenance of the robot became easier since all articulations were made of the same parts.

The cable connecting the articulation to body was exposed outside in the waterproof experimental model, but it was improved by being installed inside the articulation of leg in the lightweight model. By doing this, the waterproof connectors and pressure-resistant cables can be eliminated, so that a lighter structure is realized. Since the cable is not exposed outside, break of cable due to the impact with obstacles can be prevented, enhancing its reliability in port areas where there are many floating objects.

(3) Walking performance

Because the fluid resistance and inertial mass were reduced, a walking speed of 8.9 m/min. was achieved in the walking experiments on the plane in water tank.

4.4 Comparison of Experimental models

Table 6 shows comparison of the three experimental models which had been developed.

Table 6 Underwater Position Measurement System

Method	Long Base Line
Frequency	40 kHz~70 kHz
Output Power	500W (Main Station), 50W (Slave Station)
Way of Propagation	Linear FM
Modulate Method	Pulse Compression
Range	Within 300m
Accuracy	±0.1 m
Resolution	0.01 m

5. On-board Equipment

5.1 Underwater Position Measurement system

We developed long base line type ultrasonic transponder as an underwater position measurement system for the waterproof experimental model. This underwater position measurement system comprises a master station, 2 or 3 slave stations and a controller. The master station is put in the body of robot, and slave stations are installed at the known position on sea floor. Position of robot is measured from the response time of slave stations tot he ultrasonic wave signal from the master station. This underwater position measurement system utilizes linear FM signal, which is adopted only infrequently in the sound area, as the propagation method; pulse compression method is adopted or modulation method thereby reducing multiple reflection for obtaining a high accuracy. Shimonoseki Machinery Office, Fourth District Port Construction Bureau was in charge of developing this system. Specifications of underwater position measurement system is shown in **Table 7**, and the master station placed in the robot is shown in **Photo. 6**.

5.2 Underwater TV Camera

The main body of the waterproof experimental model is equipped with a manipulator having three degreees of freedom and a TV camera that can be attached to the tip of the manipulator. Two kinds of optical underwater TV cameras combined with the ultrasonic measuring equipment were developed as exclusive underwater TV cameras. The Niigata Machinery Office, First District Bureau of Port Construction was in charge of the development. One is a camera combined with a pulse echo type ultrasonic range finder. Using this equipment, the distance from camera to the center of the object is measured. Scales in both horizontal and vertical directions are super-impose-displayed on an underwater TV screen by calculations from the distance and the angle of view. And the dimensions of object are measured on the screen by using

Table 7 Main Specifications of Underwater TV with Ranging Device

Camera	Color (CCD) and White and Black (Visicon) Resolution 320 (Color), 500 (W&B) Minimum Brightness 30 Lux (Color), 0.3 Lux (W&B) Lens Underwater use only F1.7 Water tightness -100 m Weight 2 kgf (in the water)
Light	Halogen 650W × 2
Range Finder	Pulse Echo Frequency 500 kHz Range 0.5~7 m Accuracy ±2.5 cm
Controller	Monitor 14 inch (Color), 12 inch (W&B) Dimension 1,100 mm (W) × 1,500 mm (H) × 650 mm (D) Weight 270 kgf

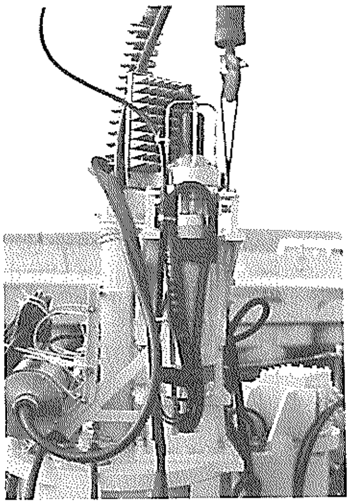

Photo. 6 Appearance of the Master Station of Transponder

cursor. The appearance of this underwater TV camera finder is shown in **Photo. 7** and its specifications in **Table 7**. Another TV camera which was developed is combined with distance measuring equipment which measures the distance by dividing the central portion of the object in horizontal direction by electronically sweeping the ultrasonic beam. This camera can display the unevenness of the subject on the TV screen. The appearance of this underwater TV camera is shown in **Photo. 8** and the specifications in **Table 8**.

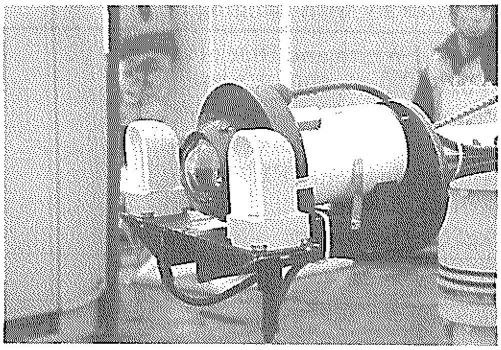

Photo. 7 Appearance of the TV Camera with Range Finder

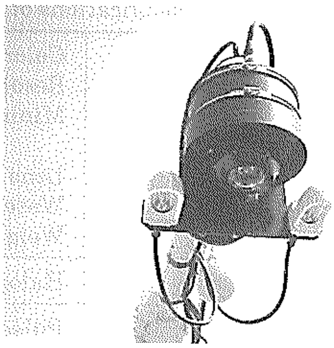

Photo. 8 Appearance of the TV Camera with Shape Finder

Table 8 Main Specifications of Underwater TV with Unevenness Measuring Device

Camera	Color (CCD) and Black and White (Visicon) Resolution 320 (Color), 500 (B&W) Minimum Brightness 30 Lux (Color), 0.3 Lux (B&W) Lens Underwater only F1.7 Water tightness -100 m Weight 2 kgf (in the water)
Light	Halogen 650W × 2
Unevenness Measuring Device	Ultrasonic narrow beam electronically scanned Frequency 500 kHz Distance 0.5~7 m Measuring Range (Unevenness) 2 m Angle of Vision ±20 degree Resolution 2 cm
Controller	Monitor 14 inch (Color), 12 inch (B&W) Dimension 1,100 mm (W) × 1,500 mm (H) × 650 mm (B) Weight 270 kgf

6. Field Tests and Its Results

6.1 Outline

Field tests using the waterproof type experimental robot in port areas have been conducted three times up to now. The field experiments were carried out by the Yokohama Machinery Office, the Second District Bureau of Port Construction. The first field test was conducted in the Yasuura District, Yokosuka Port, Kanagawa Prefecture from December 2~11, 1987. The walking experiment area (5 × 15 m) was located next to revetments. Mainly, the basic walking function was verified, and observation by the TV camera with ultrasonic range finder was performed. For the first time ever, an articulate type walking robot succeeded in walking on the sea bed. The walking speed was about 20~30 cm/min. A foot was sometimes caught in rubble mound and the joint output power was not enough. Based on the results of this test, a higher output was given to the joint actuator and the foot shape was improved. Experimenting situation is shown in **Photos. 9~10.** Second field test was conducted at the same place in Yasuura District, Yokosuka Port, Kanagawa Prefecture from March 6~13, 1989. An experimental robot which was remodeled based on the first field test results was used. Guided walking, unevenness measurement, and observation was made using the underwater TV camera with ultrasonic uneven shape measuring equipment, also, the optimum foot shape was verified. It was confirmed that maximum walking speed was 1 m/min., guidance accuracy was about 1~28 cm, the shape of walking surface was measured by the unevenness measuring function; the walking performance was considerably improved compared to the first test. The place of first and second tests was the rubble mound for which divers performed leveling work, and the leveling accuracy was 30 cm and water depth was about 5 m. In the second field test, the walking performance of the waterproof experimental robot was confirmed on rubble mound which was leveled by manpower at a low water depth. Therefore, the third underwater walking test was performed in order to confirm the feasibility of adapting the robot for practical use on the rubble mound leveled by machine with a water depth exceeding 20 m. The third field test was conducted on February 14~23 in 1990 mainly for guided accuracy, walking speed, surface scanned walking function and unevenness measuring accuracy. And video records from observation by ordinary underwater TV camera super-imposed with location information were made. Location of experiment was the Izumi Work Base in Kamaishi Port, Iwate Prefecture. Experiment site is shown in **Fig. 11**. Area for walking test was 42 × 77 m and was located adjacent to the caisson yard for the construction of the entrance breakwater of Kamaishi Bay. This place was a temporary caisson storing yard until setting caissons. The sea bed was the rubble mound leveled by a rubble mound leveling machine developed by the Yokohama Machinery Office, second District Bureau of Port Construction.

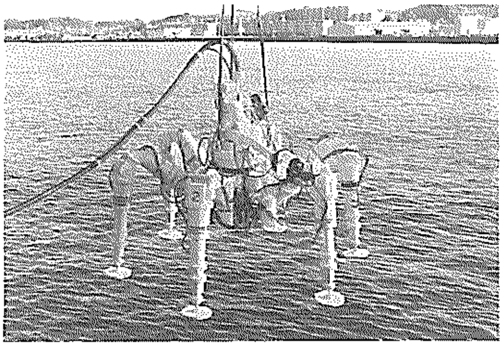

Photo. 9 Experimenting Situation (at Yokosuka Port)

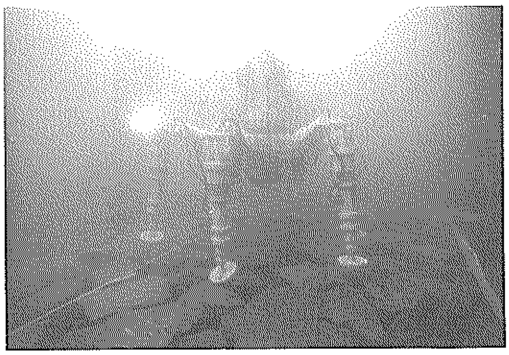

Photo. 10 Experimenting Situation (at Yokosuka Port)

According to the results of measurement of unevenness at 30 cm pitch by divers, it was 10 cm at 1σ and 30 cm at 3σ, mean water depth was 24 m. The test was carried out under the same conditions as real construction work. Samples of tests are shown in **Photos. 11~12.** All tests were conducted by lowering the robot to sea bed from a pontoon with crane.

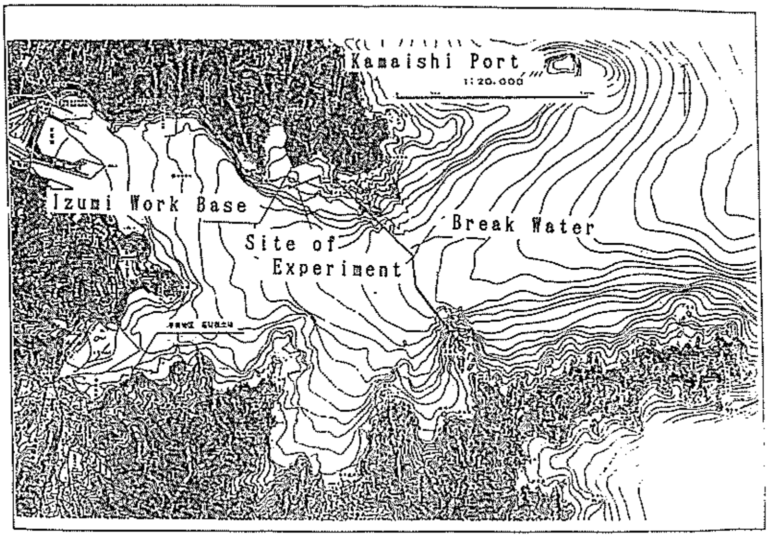

Fig. 11 Location of Experiment (at Kamaishi Port)

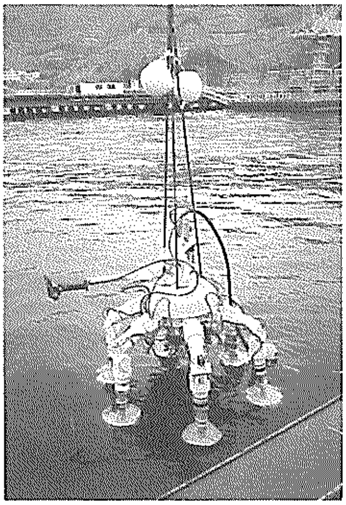

Photo. 11 Experimenting Situation (at Kamaishi Port)

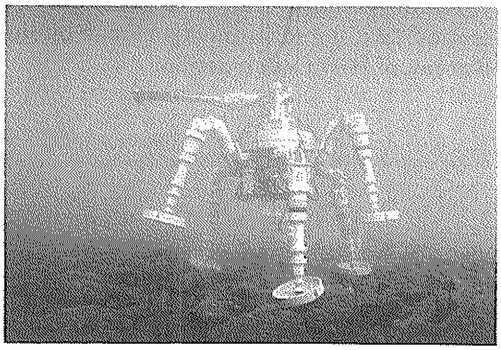

Photo. 12 Experimenting Situation (at Kamaishi Port)

6.2 Guided Walking Test

(1) Method of Experiment

A steel plate was placed on the rubble mound in advance as a mark, and its location was measured with a transmit instrument and a staff. This mark was used as the arrival point or passing point during walking. Location at arrival time or passing time was measured with underwater location measurement system and also observed with underwater TV camera. **Figure 12** shows the location of steel plate as mark. This steel plate measured 0.9 × 1.8 m. The guided walking test was carried out in the following manner: The present position data were obtained by communicating

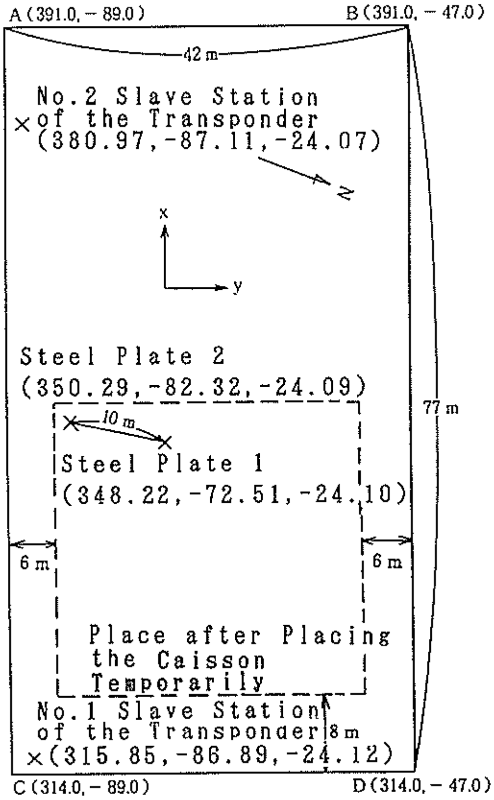

Fig. 12 Location of Steel Plate as Mark

with the underwater position measurement system every two steps. By using the data, the robot was programmed to maintain a straight path from its present position to the walking target point. The robot walked by using the internal coordinate system until the data of the underwater position measurement system were updated. Walking was terminated when the measured value of underwater position measurement system was within 10 cm from the walking target point. The walking locus maps shown in 6.2 and 6.3 are not the measured values received by the Aquarobot from the underwater position measurement system but the measured values recorded in equal time intervals by the underwater position measurement system. Because of this, if the Aquarobot stopped its body for changing the steps of legs, then the measuring points increased there. Fine fluctuation is the change in measured values by the underwater position measurement system and is not the fluctuation of the walking path of Aquarobot.

(2) Accuracy of Positioning

Six cases of walking tests between steel plate 1 and steel plate 2 were carried out, and ten tests of walking to steel plate 1 or steep plate 2 as walking target points from the random points were carried out; making a total of 16 cases. Except one case when the communication conditions of underwater position measurement system were poor, it was confirmed by the diver's TV or TV equipment on board in Aquarobot that the

Table 9 Accuracy of Guided Walk and Walking Speed

No.	Pulse Rate	Stride (cm)	Height of step (cm)	Start point (cm)	Destin-tion (cm)	Reached point (cm)	Error (cm)	Distance (m)	Time (m's)	Speed (m/min)
17-4	1/3	15	35	X 35,030 Y -8,223	X 34,821 Y -7,251	X 34,816 Y -7,264	-5 -13	9.83	16'20	0.6
17-5	1/3	20	35	X 34,816 Y -7,264	X 35,029 Y -8,232	X 35,044 Y -8,218	15 14	9.81	15'02	0.65
17-6	1/2	15	35	X 35,040 Y -8,190	X 34,821 Y -7,251	X 34,822 Y -7,249	1 2	9.66	14'55	0.65
17-7	1/2	20	35	X 34,822 Y -7,249	X 35,029 Y -8,232	X 35,037 Y -8,231	8 1	10.05	13'10	0.76
18-2	1/3	20	35	X 34,826 Y -7,254	X 35,029 Y -8,232	X 35,007 Y -8,230	-22 2	9.93	13'47	0.72
18-3	1/3	20	35	X 35,007 Y -8,230	X 34,821 Y -7,251	X — Y —	— —	10.00	10'17	0.97
17-3	1/3	15	35	X 34,995 Y -7,946	X 35,029 Y -8,232	X 35,027 Y -8,206	-2 26	2.62	7'15	0.36
17-1	1/2	20	35	X 34,536 Y -8,232	X 35,029 Y -8,232	X 34,909 Y -8,218	-120 14	3.73	5'49	0.64
17-1	1/2	20	25	X 34,870 Y -7,610	X 34,821 Y -7,251	X 34,815 Y -7,279	-6 -28	3.36	4'20	0.78
18-1	1/3	15	35	X 34,115 Y -7,040	X 34,821 Y -7,251	X 34,824 Y -7,252	3 -1	7.40	11'48	0.63
18-5	1/2	15	35	X 35,543 Y -8,010	X 35,029 Y -8,232	X 35,046 Y -8,197	17 35	5.31	8'00	0.66
18-7	1/2	20	35	X 34,866 Y -8,325	X 34,821 Y -7,251	X 34,808 Y -7,234	-13 17	10.93	13'19	0.82
19-1	1/2	20	35	X 35,004 Y -7,347	X 34,821 Y -7251	X 34,789 Y -7,236	-32 15	2.42	2'45	0.88
19-4	1/2	20	25	X 33,991 Y -7,692	X 35,029 Y -8,232	X 35,034 Y -8,227	5 5	11.72	9'57	1.18
21-4	1/2	20	25	X 34,514 Y -8,208	X 35,029 Y -8,232	X 35,013 Y -8,213	-16 19	4.99	4'41	1.07
21-6	1/2	20	25	X 34,945 Y -6,507	X 34,822 Y -7,251	X 34,846 Y -7,229	24 22	7.29	7'12	1.01
19-6	1/2	20	25	X 34,810 Y -7,372	X 32,810 Y -7,371	X 32,811 Y -7,350	1 21	19.99	23'00	0.87
21-5 -2	1/2	20	25	X 33,064 Y -7,992	X 33,000 Y -7,500	X 32,981 Y -7,504	-19 -4	4.95	3'31	1.41

Aquarobot was right above the steel plates. Coordinates at the commanded walking target points and the measured values by the underwater position measurement system at walking end point are shown in **Table 9**. Length of step is shown in the half amplitude value of the motion of the tip of leg to the main body. For this reason, the intervals of foot-mark of the same leg are "length of foot × 4." Error at the arrival position was 1~32 cm except the case where the underwater position measurement system was in poor condition. Accuracy of underwater position measurement system was 10 cm and the error of walking termination was 10 cm. The theoretical maximum error was 20 cm and it can be said that the walking is highly accurate. Walking locus between steel plates 1 and 2 is shown in **Figs. 13~17**. Walking locus is all the same and the reproducibility was good. Part of walking locus from the places other than steel plate to a steel plate is shown in **Figs. 18~23**. In each case, walking locus is on a straight line to the steel plate.

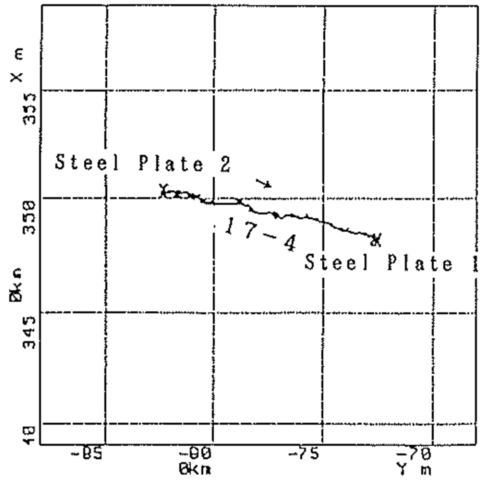

Fig. 13 Walking Locus (No. 17-4)

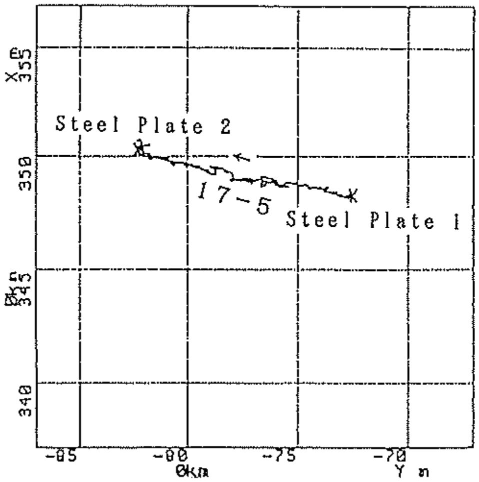

Fig. 14 Walking Locus (No. 17-5)

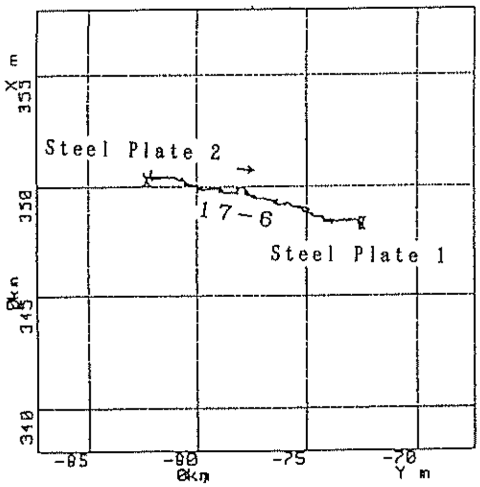

Fig. 15 Walking Locus (No. 17-6)

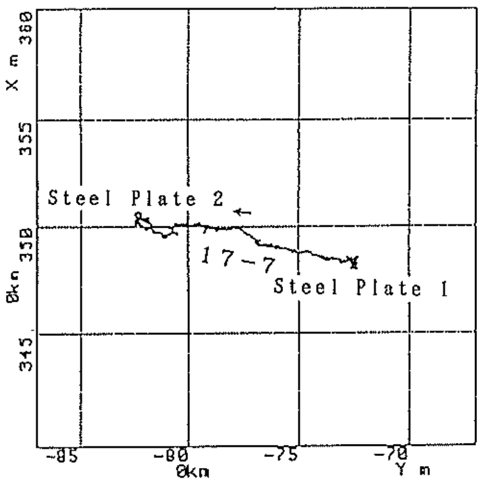

Fig. 16 Walking Locus (No. 17-7)

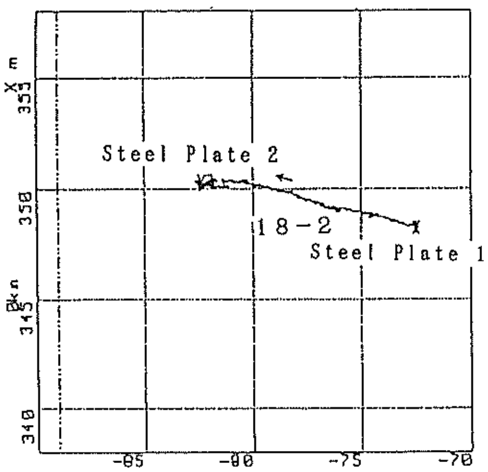

Fig. 17 Walking Locus (No. 18-2)

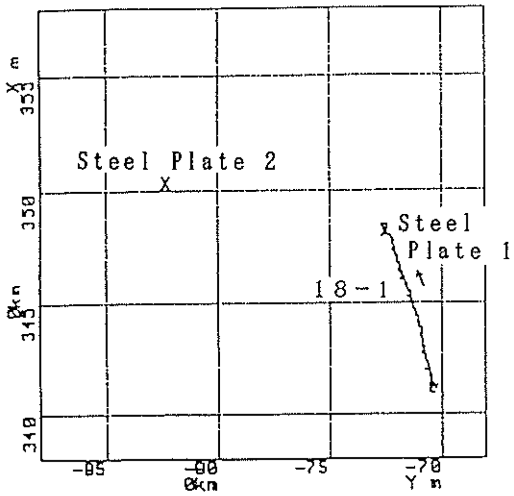

Fig. 18 Walking Locus (No. 18-1)

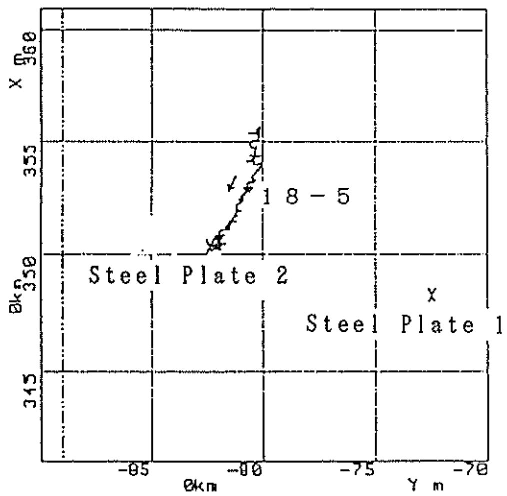

Fig. 19 Walking Locus (No. 18-5)

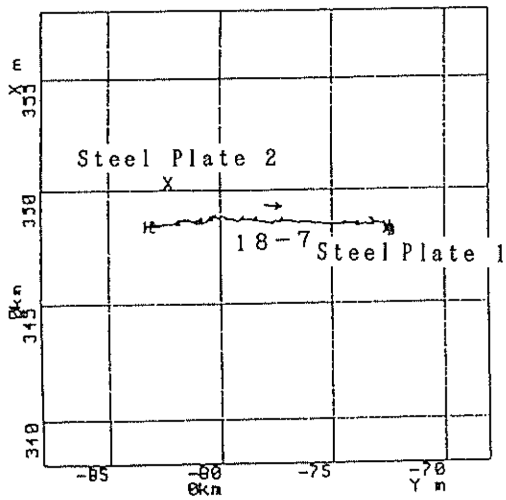

Fig. 20 Walking Locus (No. 18-7)

(3) Guidance accuracy when the position of the tip of leg is specified.

Aquarobot is guided by the measured values of master station of the underwater position measurement system placed on the manipulator, and the guidance is so performed that the center of robot body will reach the walking target point. We moved the robot in order to step on steel plate 1 with the first leg from the position 10~20 m off. The guided walk test was performed in 2 cases. In each case, foot stepped on the center of the steel plate, and error was about 1 cm and 35 cm. These values were visually measured by comparing the diameter of foot on the screen of TV camera placed in the Aquarobot.

(4) Recurrence accuracy

Walking tests were carried out by walking in various directions, instead of

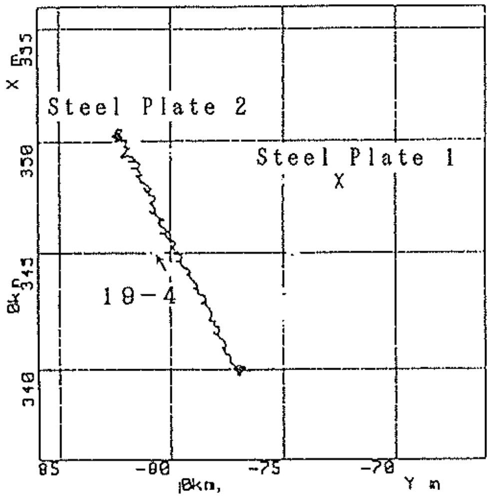

Fig. 21 Walking Locus (No. 19-4)

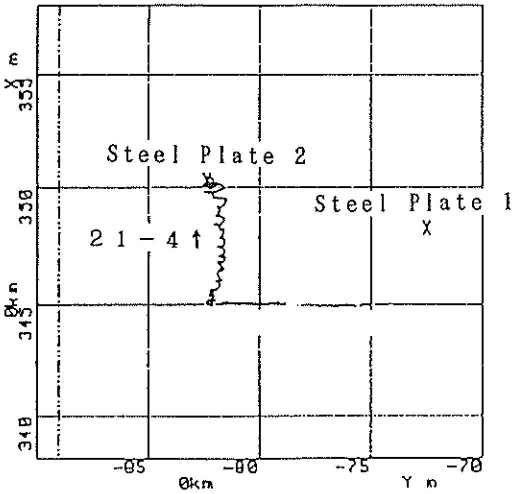

Fig. 22 Walking Locus (No. 21-4)

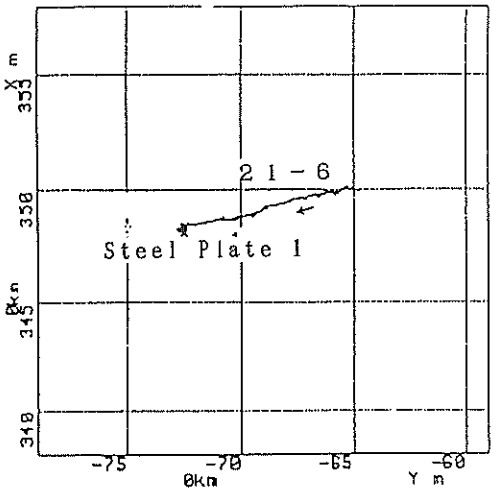

Fig. 23 Walking Locus (No. 21-6)

walking only between two points, and by returning to the original position. **Figure 24** shows the walking locus of the tests of walking on the sides of a triangle from the state of stepping on steel plate 1 with the first leg and then returning to the original position. It was confirmed that the locus returns to the walking start position not only in walking between two points such as between steel plates but also when taking alternative paths. Shown in **Fig. 25** is the walking locus of the tests from stepping on steel plate 1 with the first leg to walking to the place near the end of rubble mound and returning to the original position. In comparison with **Fig. 24**, the walking distance was fairly long. The return to the walking start position was confirmed after passing through near the base line of underwater position measurement system where the position measuring accuracy was poor. The base line of underwater position measurement system is explained in (6). Also, the direction of robot body was held

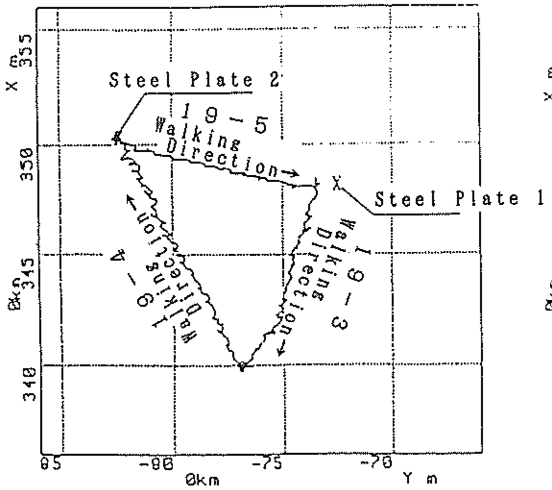

Fig. 24 Walking Locus (No. 19-3..5)

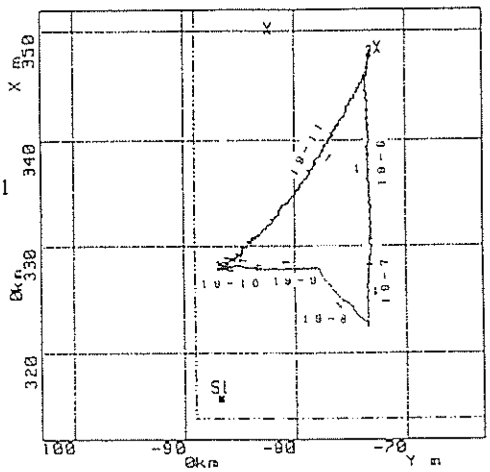

Fig. 25 Walking Locus (No. 19-6..11)

constant during tests and the robot walked in various directions. From this, it was confirmed that the Aquarobot has the same walking ability in any direction.

(5) Walking Test without Guidance

Example of walking locus without guidance by the underwater position measurement system is shown in **Figs. 26~27** for comparison with guided walking. Amount of movement of the foot was added up by the robot inner coordinate system and walk distance was calculated. The walk was terminated when the specified walk distance was realized. Position error accumulated but the azimuth error did not accumulate since the azimuth correction was made every 2 steps. For this reason, the Aquarobot can walk straight.

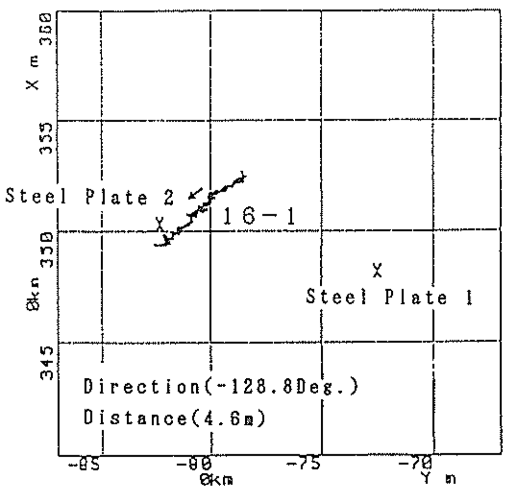

Fig. 26 Walking Locus (No. 16-1)

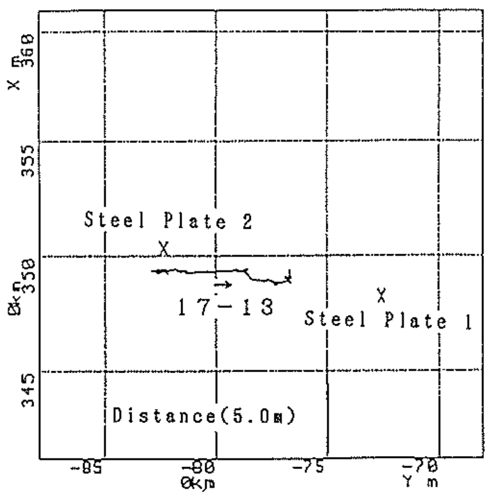

Fig. 27 Walking Locus (No. 17-13)

(6) Position measuring accuracy

The underwater position measurement system measures the distance between master station on the body of robot and slave stations installed at the known point by means of ultrasonic wave and calculates the position of robot. The accuracy changes depending on the positional relation between the slave station and robot. For instance, near base line, angle between base line (line connected between slave stations) and slant range (diagonal distance between master station and slave station) is so small that the measuring accuracy is poor in principle. In order to confirm the change in the measuring accuracy, the Aquarobot was guided for walking near the base line. The walking locus of the Aquarobot is shown in **Figs. 28~29**. In **Fig. 28**, the Aquarobot was guided from a place near base line to steel plate 1, the position of which was known. By examining the walking locus in detail, a considerable fluctuation can be seen in Y-axis direction near the base line. Guidance was performed every 2 steps so that the Aquarobot actually could not be moved in this way. This fluctuation is considered to be the fluctuation in the measured values on underwater position measurement system. As a whole, the locus reached steel plate 1 as the walking target bent. This means that error and fluctuation in position measurement system was large in an early stage of walking, and the accuracy became better as the walking continued. From the above, it can be known that error and fluctuation in the measured values by the underwater position measurement system are large near the base line but decrease as the robot moves away from the base line.

In **Fig. 29** where the Aquarobot walked parallel to Y-axis near base line, the walking locus was almost straight. It was confirmed that the accuracy of the coordinates of Y-axis vertical to the base line is poor in principle but the accuracy of the coordinates of X-axis parallel to the base line becomes better. In the case of waling in the place away from the base line, no apparent bend of **Fig. 28** was recognized. From the above, it was confirmed that the measuring accuracy is worsened near the base line. As stated above, the measuring accuracy is worsened near the base line connected between the slave station of the underwater position measurement system. This should be taken into account when arranging the slave stations of the

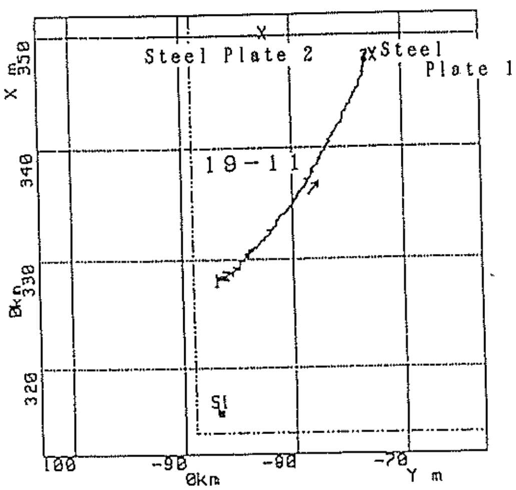

Fig. 28 Walking Locus (No. 19-11)

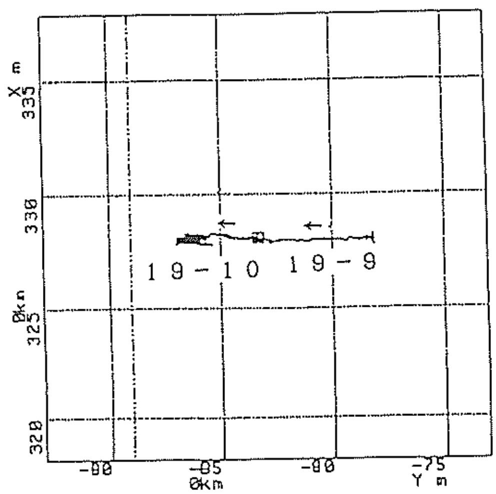

Fig. 29 Walking Locus (No. 19-9,10)

underwater position measurement system when operating the Aquarobot.

6.3 Walking Situation and Walking Speed

The walking speed changes depending on the walking parameter of the robot, the foot-raising height, length of step and pulse output speed from computer. And the speed also changes depending on the state of unevenness of walking surface. The pulse speed shows the rate of delaying by thinning-out relative to the standard pulse output speed. Therefore, the walking tests were conducted by changing the length of step, foot-raising height and pulse speed; and walking state was observed and walking speed was measured. In the test area, there were two different places to coincide with the two different stages. The first was a place where the caissons were temporarily placed and removed to other place. This place is called the temporary place. The second was a place, called the place without caissons, where the caissons had never been placed. In the place where the caissons were placed temporarily, rubble stones were pushed away and the surface was made smooth, so that the unevenness decreased and walking seemed to be easier.

(1) First stage

Forty-five walking tests at the temporary place were carried out, there was no problem in walking operation except in one case. In said case, a poor contact occurred in a connector of controller during walking. One joint moved only in one direction, so that walking was stopped. Normal operation was obtained after replacing the connector and no problem occurred thereafter. This was considered to be an accidental problem. Walking was discontinued 6 times due to poor receiving by the underwater position measurement system. Among them, the underwater position measurement system was repaired and walking was restarted on 5 occasions. Test was discontinued only once because the underwater position measurement system could not be repaired. In the walking tests at the temporary place, the Aquarobot could walk well without large inclination of the main body including the case where walking was discontinued. From the above, it was confirmed that the walking function of the Aquarobot creates no problem in the temporary place. **Figures 13~29** shows the walking locus of the temporary place test except parts of Test Nos. 1-90-10 to 11. Shown in **Table 9** are the walking parameters and walking speed at the temporary place including the walking tests between steel plates, walking tests to steel plates, and plane scanning walking for measuring line. The walking speed is the real walking speed except temporary stop time. The walking speed changes depending on the walking parameters and the situation of walking surface; for this field test, 1.41 m/min. in test No. 21-5-2 was the highest recorded speed. This was part of the plane scanning walk.

(2) Second stage

The walking tests are the place without caissons were carried out in 10 cases including the plane scanning walk, and there was no problem in the walking operation except one case. In said case, a safety device of the servo driver operated due to defective adjustment during walking, power was interrupted, and one joint became inoperative so that the walking was stopped. As a whole, the inclination of robot body tended to increase compared to the walking at the temporary place. There were depressions in the rubble mound, one leg inserted into a depression and the body inclined considerably. But the walking continued without problem. An example of the walking locus at the place before putting caissons is shown in **Figs. 30~31**. Safety device of the

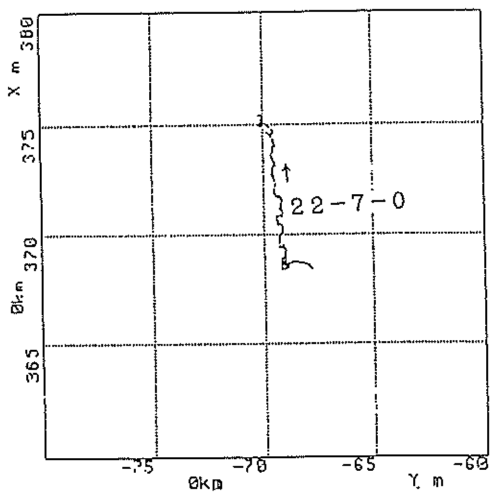

Fig. 30 Walking Locus (No. 22-7-0)

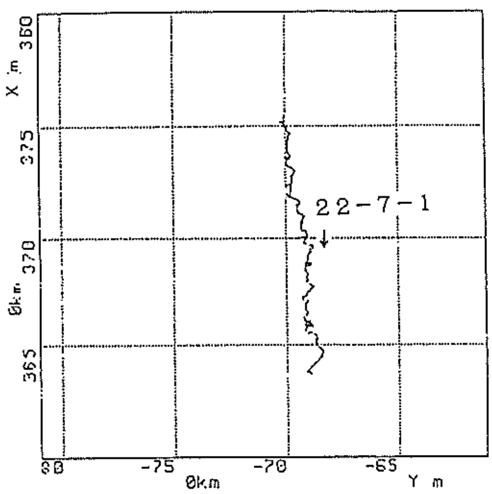

Fig. 31 Walking Locus (No. 22-7-1)

servo drive activated twice and power was interrupted. This phenomenon never occurred in the first stage. At the first case, an alarm "touch sensor is ON while the leg is raised" appeared in advance from the robot controller. But walking was forcefully continued. This alarm means that the foot-raising height was insufficient compared to the unevenness on the walking surface. Thereafter, walking was performed with the same foot-raising height at the same place and the walking was successful, so that the foot-raising height was insufficient only in a very limited area in the place before putting caissons. The second trouble occurred during a temporary stop at the place where the inter-locking of rubble was disturbed near the boundary between two places after putting caissons and before caissons. The trouble occurred at the same joint in both cases and other joints had no problem. The troubled joint was inspected and found to be poorly adjusted since maximum current limit was set smaller in this joint than in other joints. If it had been adjusted the same as other joints, then its safety device would never have been activated in both cases. Due to poor receiving by the underwater position measurement system, the walking was interrupted 4 times. Compared to the temporary place, the rate of poor receiving by the underwater position measurement system was high, but the receiving was recovered by turning the robot at the same place or turning the manipulator. This seems to occur because the relative position between the slave stations of the underwater position measurement system and the master station of the underwater position measurement system is different at the place without caissons compared to the temporary place. Real walking speed except temporary stop time was 1.14 m maximum per minute and this is slightly slower compared to the walking at the temporary place. In conclusion, more unevenness was encountered at the place before putting caissons compared to the place where caissons were already put temporarily, but the walking function was not obstructed by the irregular terrain.

6.4 Plane Scanning Walking Test

Under real working conditions for a practical robot, the plane scanning walking function will be much used since the operation is simpler. Therefore, we carried out the walking tests using the plane scanning walk function at both the place where caissons were already put temporarily and the place where caissons were not put yet. The tests were carried out by changing the width of measuring line, scanning direction and scanning start point. Walking state was observed and walking speed was measured. Planned walking path was compared to the locus of actual walking.

(1) After temporarily placing caissons

Plane scanning tests were carried out in two cases (Test Nos. 21-3 and 21-5) at the place where caissons were put temporarily.

(a) Test No. 21-3

In this test, the robot traced a U-shaped path with a walk of 10m from steel plate 2 to the positive direction of Y-axis and 5m in the negative direction of X-axis. Input values to the plane scanning walking data preparation program are as follows:

Coordinates (m) of the point at lower left:
X = 345.29, Y = -82.32
Coordinates (m) of the point at upper right:
X = 350.29, Y = -72.32
Scanning width: 5 m,
Scanning direction: Y-axis direction,
Walking start point: Upper left

The direction (upper, lower, left and right) is indicated as the positive direction of X-axis as "upper". The comparison between the measuring line commanded to the Aquarobot and the walking position obtained by the communication between Aquarobot and the underwater position measurement system during walking is shown in **Fig. 32**. Due to the performance of plotting software, the direction of x-coordinates and y-coordinates is mathematical coordinate system instead of the coordinate system using civil engineering; it is a mirror image of the actual walking locus. This was carried out by plotting the coordinate values obtained by the communication between Aquarobot and underwater position measurement system. The points as data for every two steps are different form the walking locus diagram of 6.2 and 6.3. The following plane scanning walking locus diagram is also different. The plane scanning walking is fully automatic, and there was no special problem when the walking direction

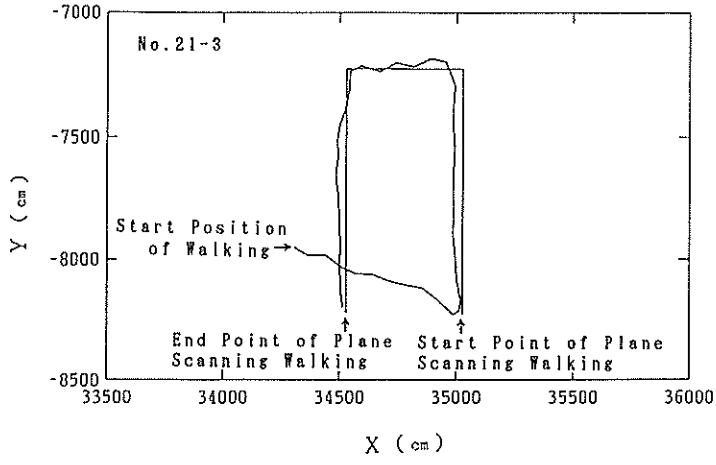

Fig. 32 Walking Locus (No. 21-3)

changed. The operator monitors only the walking situation, and his only operation was manual temporary stop because of unstable reception of the underwater position measurement system. There was no other problem and the walking function was good. Walking parameters were 120 cm of the height of body, speed of 1/2, foot-raising height of 25 cm and the length of step of 20 cm. Time which was required from the plane scanning start position to end position was 24 minutes and 35 seconds, of which the time of the temporary stop of walking was not measured but the total was about 10 seconds. Since the command walking distance was 25 m, the mean walking speed including stop time was 1.02 m/min., and the real walking speed excluding stop time was slightly higher than that.

(b) Test No. 21-5

This is the test for plane scanning of a wider range. Input values to the plane scanning walk data preparation program are as follows:

Coordinates (m) of the point at lower left:
X = 330, Y = -80
Coordinates (m) of the point at upper right:
X = 350, Y = -65
Scanning width: 5 m,
Scanning direction: Y-axis direction,
Walking start point: Upper left

The direction of upper, lower, left and right is indicated as the positive direction of X-axis as "upper".

Walking start position is the steel plate 2.

The comparison between the measuring line commanded to the Aquarobot and the walking position obtained by the communication between Aquarobot and the underwater position measurement system during walking is shown in **Fig. 33**. The walking is fully automatic, and the operator monitors only the walking situation; no operation was required by the operator during walking. Walking progressed fairly well without major problems. Operation was needed only once during walking in order to give a temporary stop for the convenience of visitors who came for study. The underwater position measurement system did not transmit the positional information five times during data recording operation due to poor receiving conditions, but the

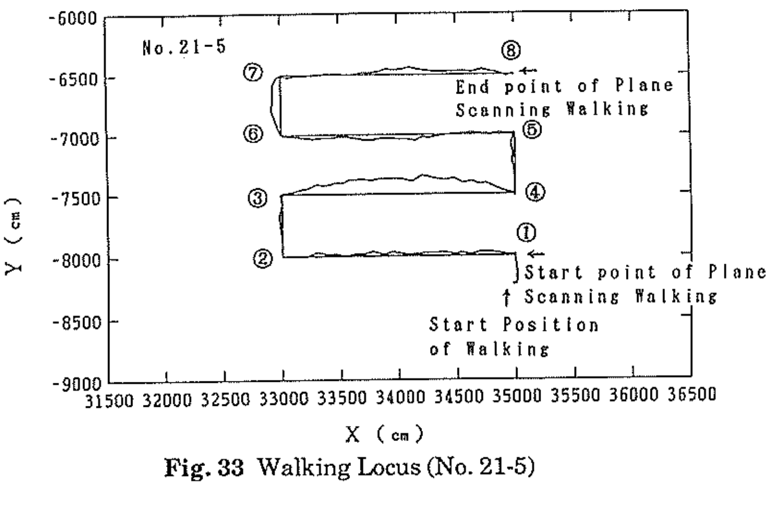

Fig. 33 Walking Locus (No. 21-5)

Aquarobot automatically stopped the walking until the positional information was received, so that no operation was needed. Walking parameters were 120 cm of height of body, speed of 1/2, foot-raising height of 25 cm and the length of step of 20 cm. Actual walking speed determined from the real walking time obtaining by excluding the temporary stop time from required time and commanded walking distance is shown in **Table 10**. Time required from the plane scanning start position to end position was 1 hour and 41 minutes and 29 seconds in which the time of the temporary stop of walking was 16 minutes and 3 seconds in total. Thus, the real walking time was 1 hour and 25 minutes and 26 seconds. Since the command walking distance was 95 m, the mean real walking speed excluding stop time was 1.02 m/min. And the real walking time excluding stop time was 1.11 m/min. Mean walking speed including stop time was 0.94 m/min.

Table 10 Walking Speed of Plane Scanning Walk

Line	Walking time (h'm's)	Net Walking Time (h'm's)	Net Walking Speed (m/min.)
1-2	23'44	15'14	1.31
2-3	3'31	3'31	1.42
3-4	22'42	19'00	1.05
4-5	4'21	4'21	1.15
5-6	19'32	19'32	1.02
6-7	9'50	5'59	0.84
7-8	17'49	17'49	1.12
Total	1'41'29	1'25'26	1.11

(2) Before temporarily placing caissons

The plane scanning walk tests at the place of before temporarily putting caissons were carried out for 1 case.

Input values to the plane scanning walk data preparation program are as follows:
Coordinates (m) of the point at lower left:
X = 355, Y = -75
Coordinates (m) of the point at upper right:
X = 375, Y = -60
Scanning width: 5 m,
Scanning direction: X-axis direction,
Walking start point: Lower left

Where, the direction of upper, lower, left and right is indicated as the positive direction of X-axis as "upper".

The comparison between the measuring line commanded to the Aquarobot and the walking position obtained by the communication between Aquarobot and the underwater position measurement system during walking is shown in **Fig. 34**. In the test No. 22-2, the Aquarobot stopped walking due to power off at servo driver as explained in 6.3 (2) on the way from measuring line 2 to 3. In test No. 23-2 to 6, the plane scanning walk was performed from the walk target point 2 already reached

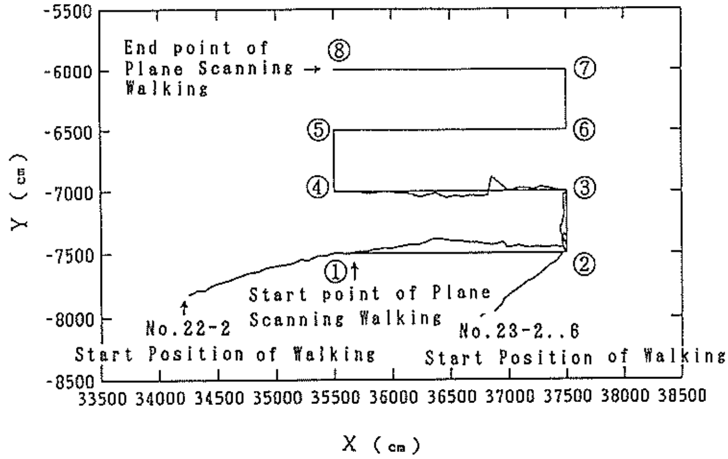

Fig. 34 Walking Locus (No. 22-2..23, /22-2..6)

before stopping the plane scanning in test No. 22-2. In test No. 23-6, the walking was terminated after reaching a place near the target point 4 because it had enough time to carry out the test. Test No. 23-2 to 23-6 was performed on the next day of the test No. 22-2, so that the walk start position and plane scanning walk start position of test No. 23-2 to 23-6 are different from those of test No. 22-2. It can be known that the Aquarobot walked along the planned route of plane scanning walk. Walking parameters were 120 cm of height of body, speed of 1/2, foot-raising height of 25 cm and the length of step of 20 cm.

Actual walking speed was 1.14 m/min. from target point 1 to 2 of test No. 22-2 and 0.99 m/min. from target points 2 to 3 of test No. 23-3 to 6. The inclination of body during walking tended to increase compared to the walking at the place after temporarily putting caissons, and unsmooth operation of the underwater position measurement system occurred frequently. But there was no other problem. Even at the place before temporarily putting caissons, the real walking speed was about 1 m/min; there seems to be no great difference in the plane scanning walk performance compared to the place after temporarily putting caissons.

6.5 Measurement of Unevenness

In order to confirm the unevenness measuring function, the irregularity of rubble mound was measured from the movement of leg during walking, the unevenness was measured by performing walking operation from steel plate 1 to steel plate 2. The distance between the two steel plates was 10 m. An example of unevenness measured values were shown in **Fig. 35.** All six legs can be measured, but these values were measured for odd-numbered legs only. Water depth at the walking start point and end point was measured by the pressure gauges in the main body, and the unevenness between the walk start point and end point was measured by the total of the motion of legs. The unevenness measured values which were shown in **Fig. 35** are within the range of 23.2 to 23.5 m. Tide level during tests was 0.67 to 0.73 m in the data of marine scale and the reference water depth at the test location was 24 m, so that unevenness measured value became considerably smaller. The results of unevenness of measurement at 30 cm pitch by divers in test location were 10 cm at 1σ and 30 cm at 3σ. The change in

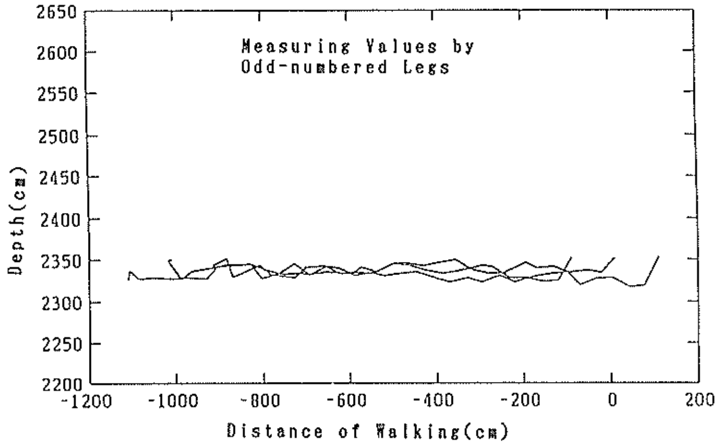

Fig. 35 An Example of Unevenness Measured Values

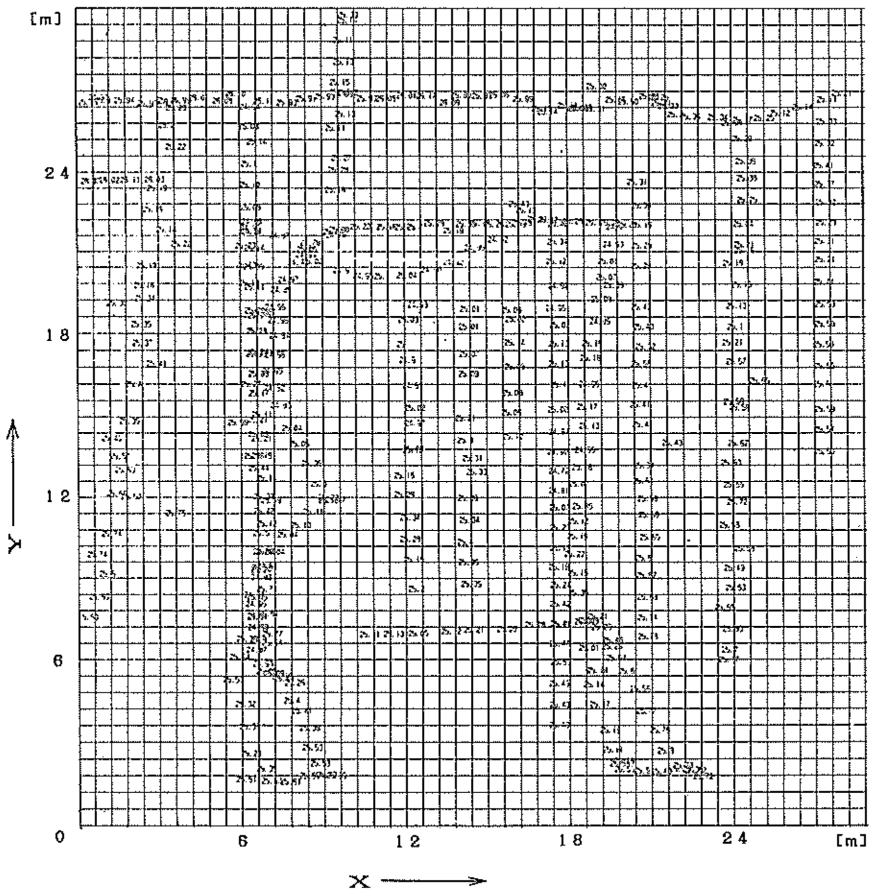

Fig. 36 Walking Locus and Measured Value

the measured values of unevenness was appropriate. From the above, errors of the absolute values of water depth measurement by internal body pressure gauges are large. But the measuring accuracy of relative unevenness by the leg movement is considered to be relatively good. Walking locus and measured values of unevenness are indicated in **Fig. 36**, which was drawn by plotter for evaluation of the surface.

6.6 Summary of the Test Results

Results of the field tests are summarized hereinafter:

(1) Walking on the rubble mound mechanically leveled at the water depth of 24 m was performed successfully.

(2) Guidance accuracy was 1~35 cm and this positioning accuracy is very high for a robot moving underwater.

(3) Walking speed varies depending on the walking parameters. It was 1.41 m/min. maximum at the place after temporarily putting caissons and 1.14 m/min. maximum at the place before temporarily putting caissons. This waterproof experimental model seems to have workability equal to or better than the work by manual labor in view of about 5 minutes per point by the 5 m pitch unevenness measurement by divers.
In the walking test on the plane within test pool, 6.5 m/min. was recorded, and the walking speed of the waterproof experimental model has a considerably high level compared to even the on-land walking robot without considering the walking within water.

(4) The practicality of the highly automated plane scanning walk function, in which the walking is sequentially performed along the measuring line automatically created after giving the width of measurement and the coordinates of apex of the area where the robot was made to walk was confirmed.

(5) In the measured values of unevenness, the errors of the absolute values of water depth were large but the measuring accuracy of relative unevenness due to leg movement was relatively good.

(6) Walking on sand floor was successful and only small disturbance of bottom material was evident.

(7) Video used for recording position information was effective for the analysis thereafter.

7. Technical Feasibility in the Future

Future technical feasibility of the Aquarobot is described below.

7.1 Compact and Lightweight

The servo drivers on the market are used in the Aquarobot. If the digital portion of the servo driver is separated from the analog portion and the analog portion is installed in the body of robot, then 18 pairs of power lines can be reduced to only one pair, by which the minimum increase of the weight of the robot is required, the cable diameter can be reduced and the size of the controller can be greatly reduced.

7.2 Improvement of the performance

By changing the control method from the existing static control to dynamic control, both the walking speed and adaptability to irregular rough terrain can be improved.

8. Concluding Remarks

Much researches is being carries out on walking robots. But the walking robots for on-land use which are produced by way of experiment have not been put to practical use. It was corroborated that the waterproof experiment machine as No. 2 Aquarobot had the practical walking capability in the three underwater tests required for practical use. The use of walking robots in sea creates the problems of waterproofing and corrosion; but the use of cable is not difficult so that power unit is not installed in the body, and there is another advantage of decreased weight by buoyancy. Successful factors of the Aquarobot were that it was applied to the working environment where the disadvantages of walking robot can be made up for, and the function possible only by the walking robot was given such as measurement of unevenness, and the purpose of use was focused on underwater inspection work taking the place of divers. We believe that the Aquarobot will become the first practical robot with walking function. According to the recent trend in the research on walking robot, most of the robots studied or practical use are the six-legged axis-symmetrical type the same as the Aquarobot. Superiority of this type was recognized. Technology established by the development of the Aquarobot may be applicable not only to underwater use but also to outer space and radioactivity and other hazardous environments. We have described the results of development of walking robot underwater inspection "Aquarobot" centering on field tests.

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