運輸省港湾技術研究所 (25th Anniversary Issue)

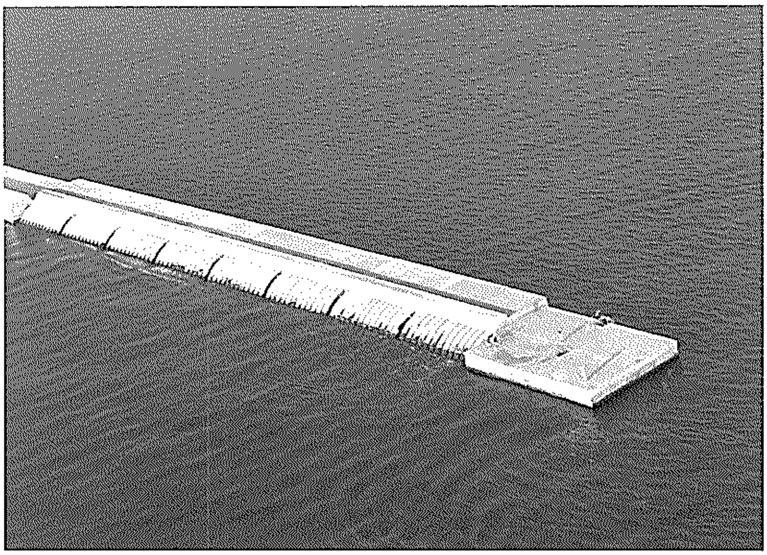
港湾技術研究所報告

REPORT OF THE PORT AND HARBOUR RESEARCH INSTITUTE

MINISTRY OF TRANSPORT

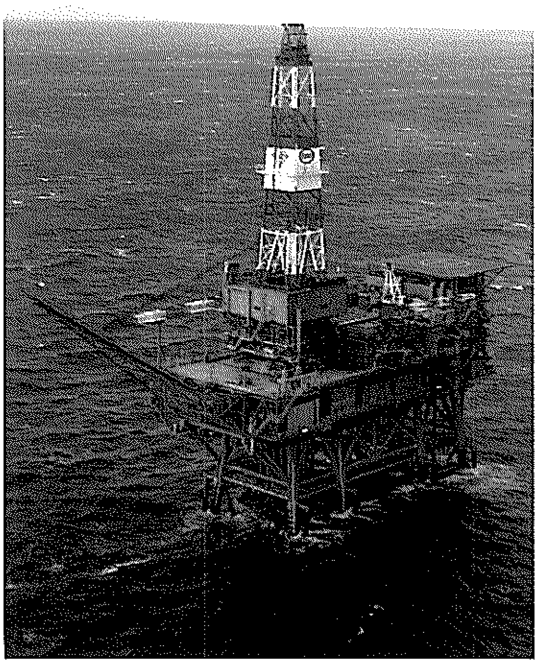
VOL. 26 NO. 5 DEC. 1987

NAGASE, YOKOSUKA, JAPAN



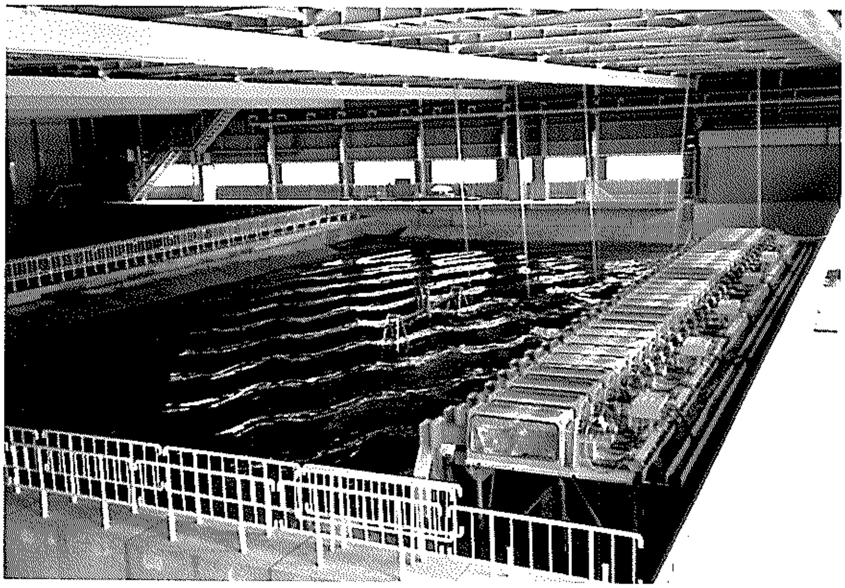
Curved Slit Caisson Breakwater

View of curved slit caisson breakwater completed in the construction at the port of Funakawa. (Courtesy of Akita Port Construction Office, the First District Port Construction Bureau, Ministry of Transport)



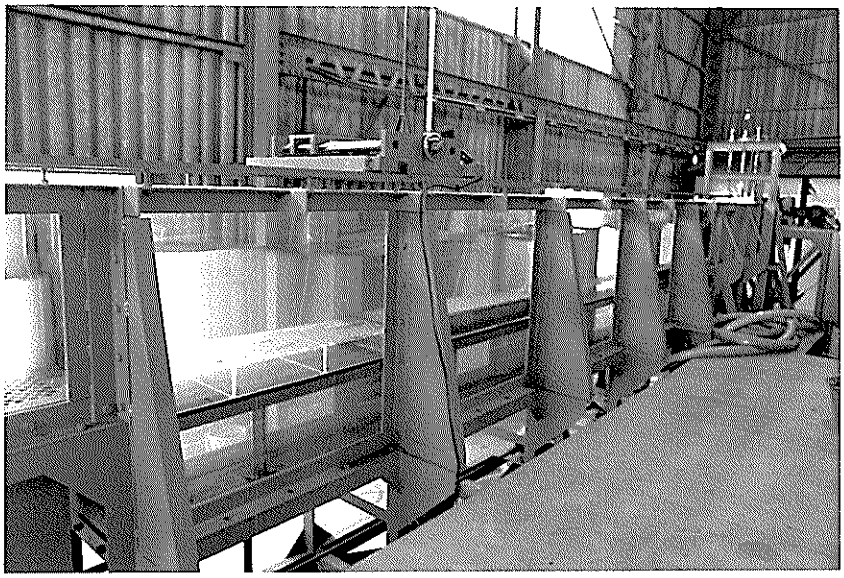
Facilities for Ocean Directional Wave Measurement

Four step type wave gauges and a two-axis directional current meter with a pressure sensor are installed on the legs of an offshore oil rig. They are operated simultaneously for detailed directional wave analysis.



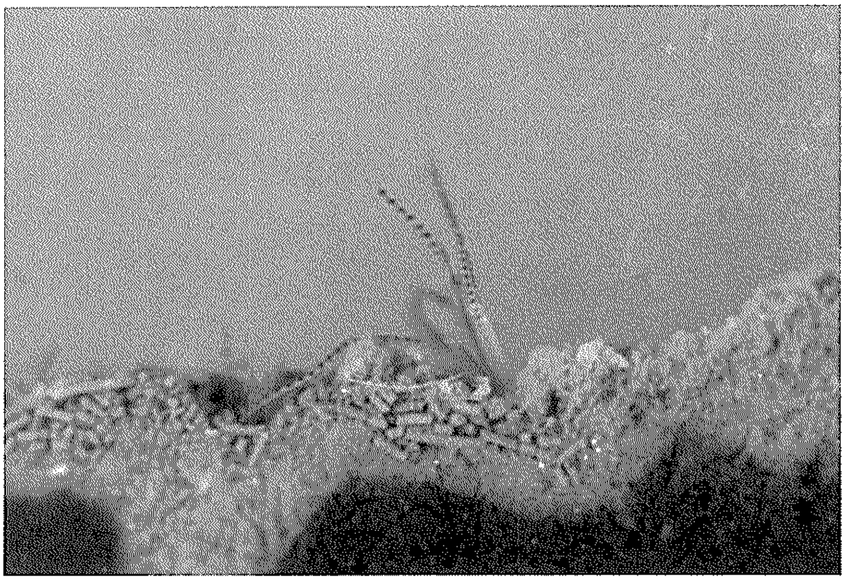
Serpent-type Wave Generator

The photograph shows the serpent-type wave generator in the short-crested wave basin and the superimposition state of two different oblique waves generated by the generator.



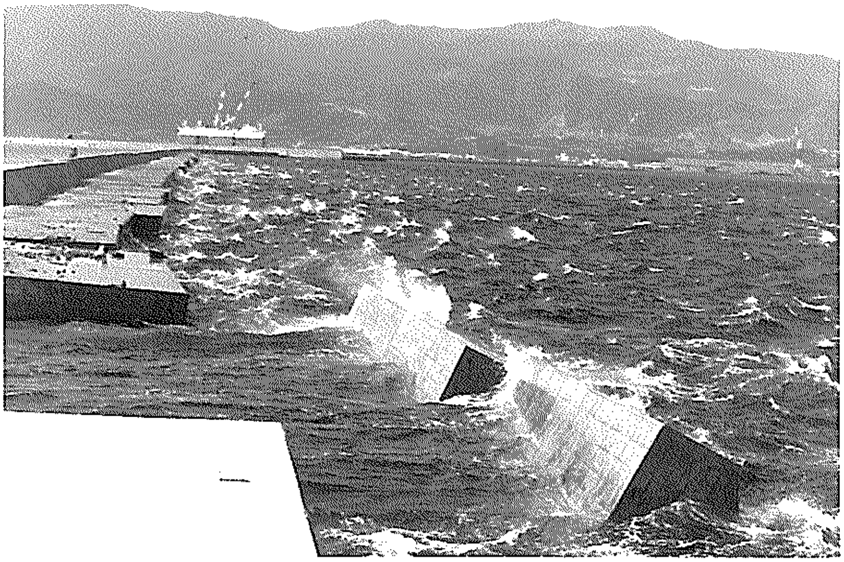
Wave-soil Tank

The experiments concerning the wave-soil interactions are conducted in this tank. The soil tank and the test section are located at the center of the tank. A movable floor is provided at the bottom of the test section and the level of the interface of mud layer and water can easily be adjusted to the level of the flume bottom.



Pararionospio Pinnata

The biomass of benthos is one of the most sensitive indices to know the effect of sea-bed sediment treatments on the marine environmental improvement. The picure shows a kind of benthos, *pararionospio pinnata,* which preferentially exists in the polluted sea-bed.



Breakwater Damaged by Storm

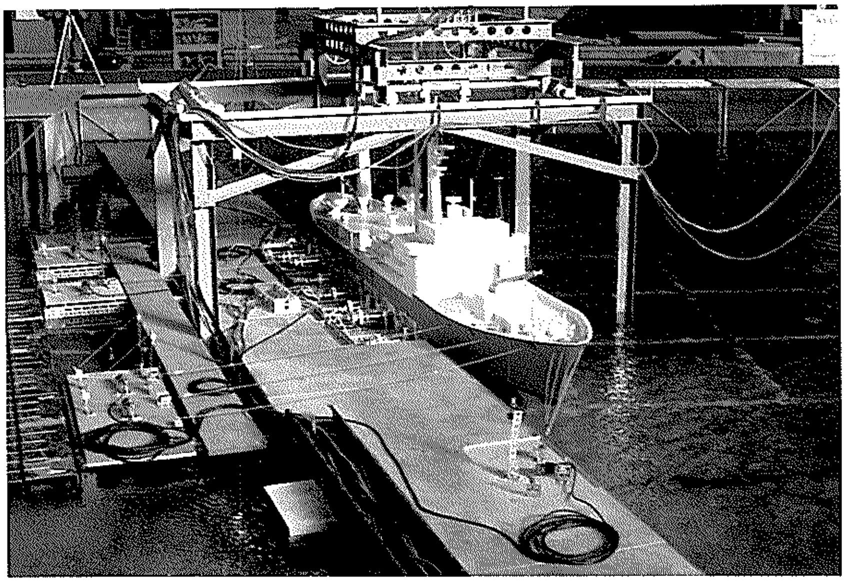
This photograph shows a breakwater damage by a storm.
The breakwater is of the composite type with concrete caisson on a rubble mound. Two caissons were severly damaged due to the instability of a rubble mound.

Nondestructive Evaluation of Pavement

Nondestructive methods for evaluating the load carrying capacity of airport concrete pavements have been developed by using Falling Weight Deflectometer(FWD).

Seismic Damage to Gravity Quaywall

The 1983 Nipponkai-Chubu earthquake(Magnitude : 7.7)caused serious damage to port facilities in northern part of Japan. This photo shows the damage to gravity quaywall. The concrete cellular block walls were collapsed and completely submerged.

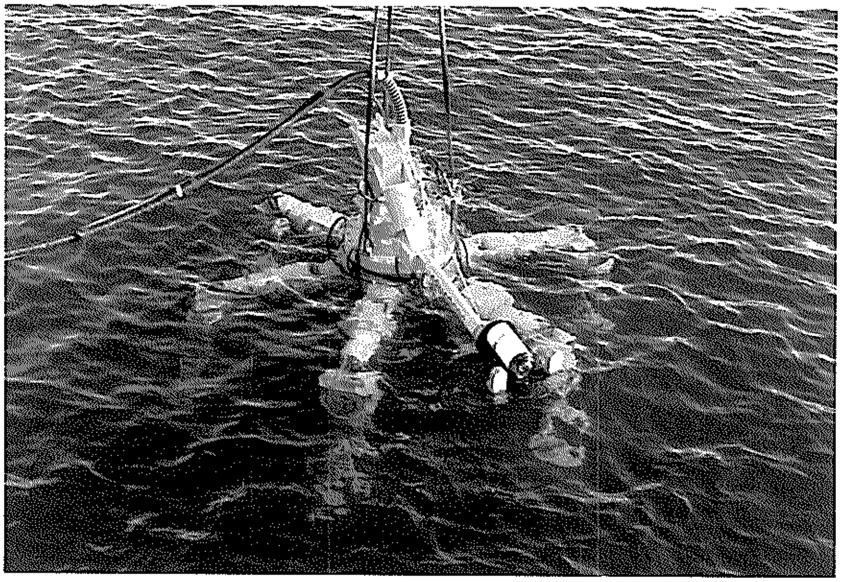


Model Experiment of Mooring Ship

Model ship is moored at a quay wall with fenders and mooring ropes subjected to gusty wind and/or irregular waves.

Vessel Congestion in Japan

As Japan is surrounded by the sea, there are many crowded water areas with various sizes and types of vessels. Arround there, many construction works were planned such as ports and harbours, off-shore airports, huge bridges and so on, so that many marine traffic observations and marine traffic simulations have been carried out.



Underwater Inspection Robot

This is the six-legged articulated underwater inspection robot named "AQUAROBOT". The robot controlled by a computer can walk on uneven sea bed without making water muddy.

Foreword

The Port and Harbour Research Institute is a national laboratory under the Ministry of Transport, Japan. It is responsible for solving various engineering problems related to port and harbour projects so that governmental agencies in charge of port development can execute the projects smoothly and rationally. Its research activities also cover the studies on civil engineering facilities of air ports.

Last April we have celebrated the 25th anniversary of our institute because the present organization was established in 1962, though systematic research works on ports and harbours under the Ministry of Transport began in 1946. As an event for the celebration, we decided to publish a special edition of the Report of the Port and Harbour Research Institute, which contains full English papers only. These papers are so selected to introduce the versatility of our activities and engineering practices in Japan to overseas engineers and scientists. It is also intended to remedy to a certain extent the information gap between overseas colleagues and us.

The reader will find that our research fields cover physical oceanography, coastal and ocean engineering, geotechnical engineering, earthquake engineering, materials engineering, dredging technology and mechanical engineering, planning and systems analysis, and structural analysis. Such an expansion of the scope of research fields has been inevitable, because we are trying to cover every aspect of technical problems of ports and harbours as an integrated body.

The present volume contains eleven papers representing six research divisions of the institute. The materials introduced in these papers are not necessarily original in strict sense, as some parts have been published in Japanese in the Reports or the Technical Notes of the Port and Harbour Research Institute. Nevertheless they are all original papers in English and are given the full format accordingly. We expect that they will be referred to as usual where they deserve so.

It is my sincere wish that this special edition of the Report of the Port and Harbour Research Institute will bring overseas engineers and scientists more acquainted with our research activities and enhance the mutual cooperation for technology development related to ports and harbours.

December 1987
Yoshimi Goda
Director General

港湾技術研究所報告 (REPORT OF P. H. R. I.)

第26巻 第5号 (Vol. 26, No. 5) 1987年12月 (Dce. 1987)

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11. Development on Aquatic Walking Robot for Underwater Inspection

Mineo IWASAKI*
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Kazumasa ASAYAMA******

Synopsis

An experimental model and a prototype model were made for the development of underwater inspection robot. The experimental model is a overground test robot that is not made watertight. The model was used for basic research and a debug tool for program development.

The prototype model made watertight was developed after tests of the experimental model. The model is the first walking robot in the world that has succeeded in walking on sea bed.

The hardware and software of the robots are described herein. The principal features of the models are as follows.

The robots named "AQUAROBOT" are six-legged articulated "insect type" robots. Each leg has three articulations and has a touch sensor on the foot. The articulation is driven semi-directly by a DC motor that is built in the leg. All the motions are controlled by a micro-computer. Therefore, the robots can walk on uneven ground and can walk in any direction without changing its quarter.

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港湾技術研究所報告
第26巻 第5号 (1987.12)

11. 歩行式水中調査ロボットの開発

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要 旨

従来の水中調査ロボットは，浮遊しながら移動する。このために，見るには適していても測ることには適していない。そこで，位置を安定に保て，見ると測るに適した歩行式の水中調査ロボットを開発することにした。

第1号機は，陸上歩行機で，歩行機能確認，ロボットの制御プログラム開発用として，製作した。第2号機は，防水仕様のプロトタイプで，世界で初めての水槽歩行及び実海域での歩行に成功した。本論文は，これらのロボットのハードウエアーとソフトウエアーについて記述している。

主な仕様は，次の通りである。

このロボットは，アクアロボとよばれ，軸対称に脚6本を持つ昆虫型の歩行ロボットである。脚長は，第一号機が85cmで，第二号機が1.5mである。各脚は，3個の関節を持ち，足先は接地センサーを持っている。

関節は，脚内に搭載された直流サーボモータで駆動される。ロボットの動きは全てマイクロコンピュータで制御されるために，ロボットは，凹凸のあるマウンド面の歩行と登はんが可能で，体の向きを変えないで任意の方向に歩行する能力を持っている。

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****機材部 特殊作業船開発室
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Contents

1. Introduction

Many ROVs (remotely operated vehicles) have been developed but most move while floating in the water. It is difficult for the ROV to maintain a stationary position and direction. ROV are good on observation with a TV camera but are weak in their capacity to measure objects with accuracy. There are some vehicles that can move on the sea bed with wheels or crawlers. These vehicles can maintain their positions and directions stationary but movement of the vehicles makes the water so muddy that the TV cameras can not be used. There is no underwater robot in the world that has the functions of observing and measuring in the water.

However, we thought that the walking robot controlled by a computer could walk on uneven sea bed without making water muddy. We decided to develop an underwater walking robot that has both the functions of looking and measuring. This robot is placed in the category of intelligent robots and the development of this robot demands new technology of robotics.

Many kinds of robots are working in factories, but some people think that the factory robot is not an intelligent robot but only an automatic machine, because the robots have only the ability to repeat the same operation.

Types of walking robots were researched and made for testing. The aim of this research is to develop a robot that can walk on uneven places where wheels cannot be used.

R. B. McGhee developed two walking robots "OSU-HEXAPOD" but it was published in a newspaper that the second robot failed to walk. M. H. Reghbert made a robot that can walk with an operator on the body but video movies[3] showed that the robot could not walk according to the operator's will. "ODEX 1"[2] is the most famous walking robot. If the robot is to be adapted to underwater inspection robot, then the following problems will have to be solved.

The robot is not watertight and the structure and mechanism of legs are not suitable for watertight designs. The robot is slender and tall. A robot with a high center of gravity has no problems for walking on the ground but the shape becomes important for walking on the sea bed as the forces of water current are so large that the robot is made unstable. The technical level for walking robots are far from practical use and there are no real plan to use the robots. Moreover, there is no underwater walking robot in the world. We therefore challenged the development of an underwater walking robot to carry out the underwater inspection works.

The prototype model we developed succeeded in walking on sea bed. This success is the first in the world.

2. Features of the Robot

There are two kinds of underwater works in port construction. One is the work for inspection, while the other is the work for construction itself. In Japan, the government or the port authority is usually the orderer of constructions. Underwater inspection works are carried out usually by the orderer and the aim of this kind of works is the supervision of constructions, quality control, inspection of structure and the search for mines. Private companies are usually the receiver of orders and they conduct construction works. Our institute belongs to Japanese government and research for an underwater inspection robot was therefore started in 1984.

2.1 Comparison of Underwater Inspection Robots

All underwater robots can be divided into three types. Table 1 is a comparison of the three type underwater robots.

Table 1 Comparison of underwater robots

	hanging type	floating type	moving on sea bet type
moving method	by hanging strings	by screw	by wheels, crawler or legs
positioning in tidal current	bad	bad	good
accuracy of positioning	bad	bad	good
usage	observation	observation	observation & measurement

One function of the robot is inspection to the same accuracy as divers. The first necessary function is that the robot moves with good accuracy and can keep its position during measurements. Both the hanging type and the floating type do not have this function and only the type that moves on the sea bed can have the function.

The move on sea bed type robots are divided into the four types that are wheel type, crawler type, Archimedean screw type and walking type. Table 2 shows a comparison of the type that moves on the sea bed.

Another important function is that robot can move without making the water muddy for the use of underwater TV.

The wheel type crawler type and screw type robot make water muddy, and so these types are not suitable as inspection robots.

The structure or type of robots differs between underwater survey robots and underwater construction robots. Construction robots become heavy when they have strong force, but it is better for survey robots to be smaller and lighter.

To move on uneven ground of rocks, the radius of the wheel becomes very large, therefore the wheel type robot becomes big and heavy, and the crawler type is the same as wheel type robots. The screw type robots are useful only for moving on soft sea beds and so the area where the robot can move is limited.

The walking type robot have a high capability to walk on uneven rocky ground when compared with its body size. These type of robots can walk with making water little muddy.

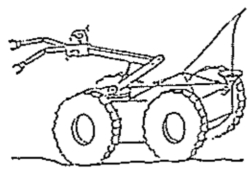
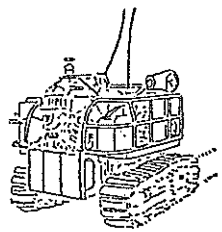
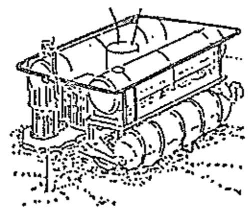
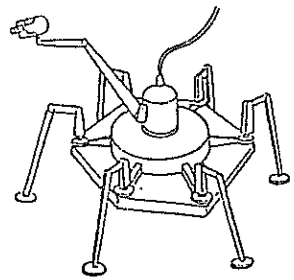
For these reasons, it seems to us that the leg type is the most suitable for underwater inspection robot without thinking of technical problems.

These technical problems must be solved by progressive robotics technology.

2.2 Comparison of Walking Robots

There rae two kind leg structures for walking robots. One is the so-called

Table 2 Comparison of moving on sea bed types

	wheel type	clawler type	screw type	walking type
dimension	big	big	middle	small
weight	heavy	heavy	light	light
direction of move	forward & backward	forward & backward	forward & backward	all direction
ability of moving on uneaven sea bed	low	high	low	high
muddiness made by move	much	much	much	few
usage of underwater TV	impossible	impossible	imposible	posible
				

"mammal type" that always keeps its legs vertical like a horse. The other type is the "insect type" that always has its legs bent like a beetle. It is said that insects can walk more easily on uneven ground than animals, if the bodies are same size. Therefore, if two robot are designed to walk on the same uneven ground, the insect type robots are inherently smaller than the mammal type robots. It can be said that insect type robot is suitable for underwater walking inspection robot.

There are two methods of controlling the leg motions. One is the mechanical control method, the other is the software control method. Mechanical control is often used for toys where the legs move repeatedly by mechanical devices. Therefore, the motion of the legs is finite. In the early research of walking robots, some research were performed for mechanical controlled walking robots. However, there were no mechanical controlled robots that could walk on uneven ground.

The softwawre controlled robots have legs that can moved anyway by computer. Therefore, the motions of legs are infinite. In return for the merits, high technology software has required for robot control.

Recent research into walking robots is almost all for the software controlled type and some of these robots have succeeded in walking on uneven ground. Therefore, it can be said that the software control is the only method for underwater inspection robots to walk on uneven sea bed.

The number of legs is one of the most important factors for walking robots and the robots already researched have one, two, four, six or eight legs.

If the number of legs is one, two or three, dynamic control must be used to keep the robots standing. For four legged robots[1)], dynamic control is not needed but the monitoring of center of gravity is necessary. If the number of legs is six, or eight, both the dynamic control and the monitoring of center of gravity are not needed.

It is said that walking speed of six legged robots must be highest for insect-type walking robots because there is much dynamic control or the monitoring of center of gravity and eight legs are too many for leg control without interference. A six legged robot is suitablt for underwater survey robot.

In a six legged robot, there are two different arrangements of legs, one is the robot that has three legs respectively on both the right and left side of a rectangular body. The other is the robot that has legs arranged axsi-symmetric around the body. The axsi-symmetric robot can walk in any directions without changing the direction of the body and can easily turn the body within its own space. These functions are useful for underwater inspection robots when they walk on an uneven sea bed.

2.3 Features of the Robot

From the reasons mentioned above, it was decided that an underwater robot type should be the "axsi-symmetrically six-legged, software controlled insect type walking" robot.

In addition to the robot type, the functions that the target robot must have was decided at the same time. The functions are as follows.

a. The robot must be designed to be as small and light as possible.
b. The robot can walk on uneven rock mound and can go to a point with high accuracy and can keep its position.
c. The robot can measure the level of rock mound by analyzing the legs motions. Namely, the walking is the measurement itself.

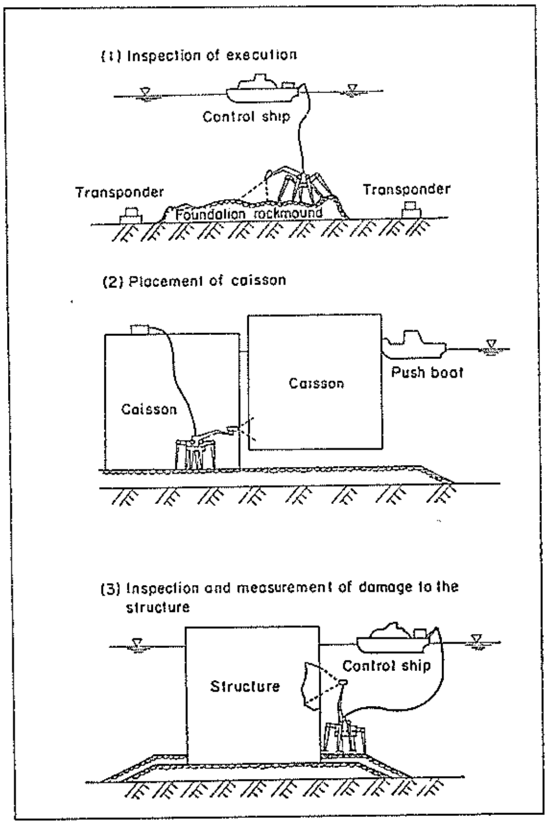


Fig. 1 Underwater operations of the robot

d. The robot has a wide space for instruments.
e. The robot has a TV camera and a manipulator.
f. The command from the operator are only direction and distance. The robot is so intelligent that the robot can walk on uneven ground by itself.

Figure 1 shows the expected work of the underwater survey robot.

3. Experimental Model for Overground Test

We decided upon these features of the target robot in 1983. These features are ideal for an underwater walking robot. Therefore, there were many problems in realizing the ideal robot.

The first research on the robot was for the structure of the articulations and the motor control method.

The articulation test apparatus was made and the applicability of the articulation was tested. This apparatus consists of an articulation and an 8-bit micro computer. Photo 1 shows the apparatus.

After this basic research, we developed an experimental walking robot in 1985.

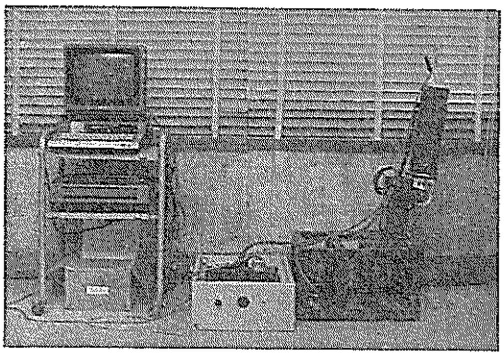


Photo 1 Articulation test apparatus

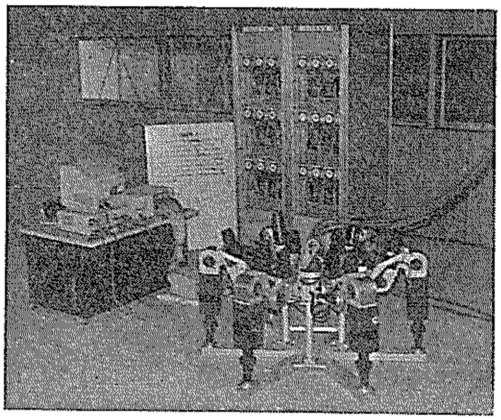


Photo 2 Experimental model and controller

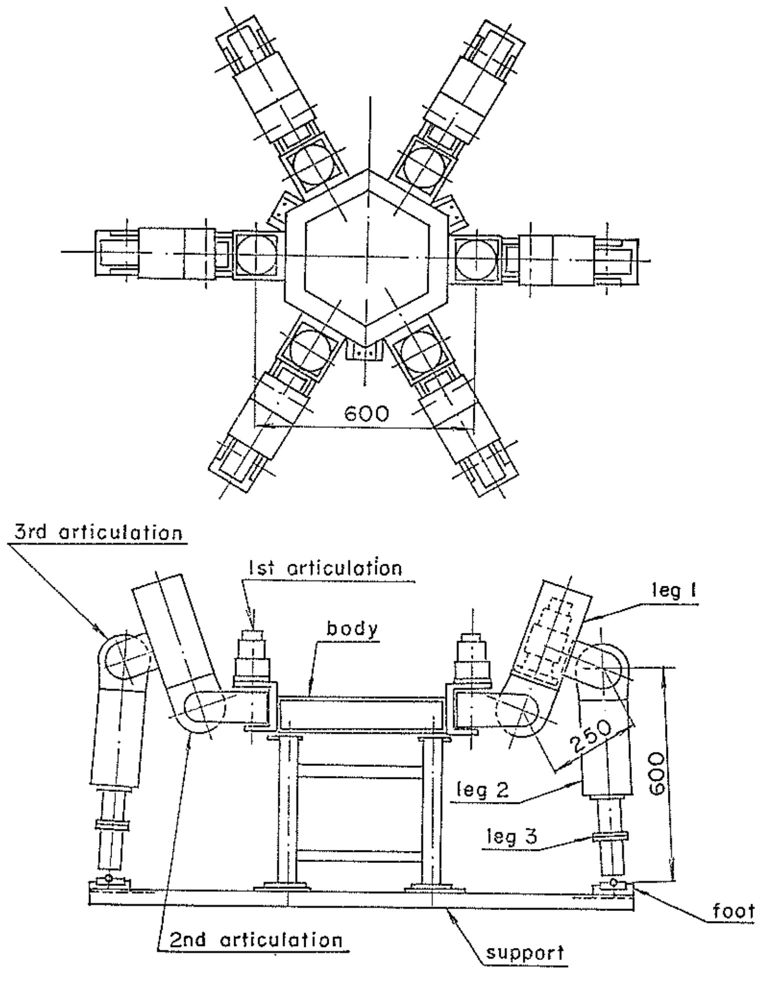


Fig. 2 Dimension of the experimental model

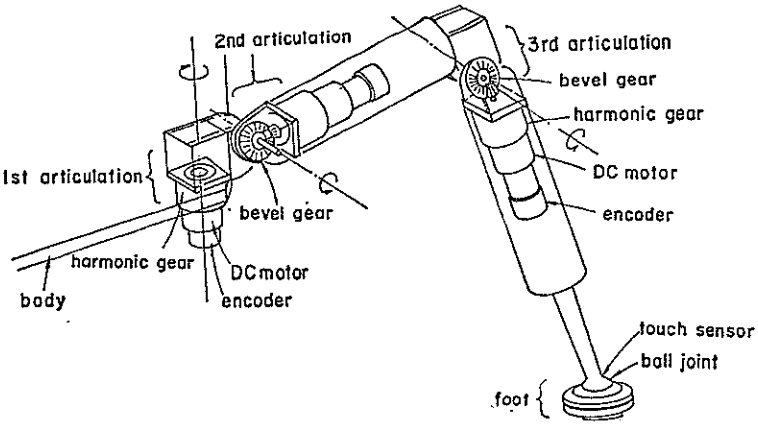


Fig. 3 Structure of leg

Figure 2 and Photo 2 show the experimental walking robot named "AQUAROBOT".

3.1 Structure Members of the Robot

The structure of the robot consists of a body and legs.

(1) Body

The body is hexagonal in shape and made of anti-corrosive aluminum. The legs are installed on the sides of a hexagonal frame 60 cm across and some sensors are installed on the body.

(2) Legs and Articulations

The legs of walking robots controlled by a computer are very similar to the manipulators of industrial robots. The minimum degrees of freedom to move the point of a manipulators anywhere is three. Therefore, a leg consists of three articulations, rather, each leg has three degrees of freedom.

Figure 3 shows the leg structure of the experimental model for the over ground test. The rotating axis of the first articulation that is nearest to the body is vertical and the axis of the other articulations are horizontal. A foot and a leg are linked with a ball joint. A foot has a touch sensor.

The length of the thigh and the shank is 25 cm and 60 cm respectively. The legs are made of anti-corrosive aluminum.

The articulations are driven by DC motors with gears. This drive method is called a semi-direct drive mechanism. The gears are harmonic and bevel gears and the gear ratios are respectively 160 and 3. This semi-direct drive mechanism is so simple that the watertightness of the articulation can be achieved by sealing one shaft. All of the driving devices can be installed in the legs that are also watertight cases.

This structure differs from that of the existing walking robots ODEX-1[2] and TAITAN-3[1] as these robots have link mechanism. If the link mechanism is used in an under water robots, the screw to move the link mechanism is always exposed in the water, making it difficult to prevent erosion of the screw. Therefore, the semi-direct drive mechanism is most suitable for underwater robots.

Recently, there has been much research into the direct or semi-direct drive mechanism because this mechanism is simple and it is easy to make articulation modules. Therefore, this mechanism has the potentiality that any kind of robots can be made by assembling the modules. However, robots with this mechanism are only used for small industrial robots now because of the difficulty of making firm articulations.

There are some differences between the legs and manipulators from the design point of view. It is an well known fact that the motors are often installed on the ground to make the arms of industrial robot lighter. It is a reason why the heavy arm demands more high power of motors and makes robot more heavy. However, in the walking robot, the tops of arms are the feet of legs are always touching the ground. Since most of the legs' weight is always on the ground and heavy parts like motors must be installed in the legs.

The two different method of installation come from the same theory that heavy parts must be loaded on the ground side.

(3) Estimation Method of Articulation Torque

In the first stage, we estimated an articulation torque disregarding the foot friction. This method is shown in Fig. 4. In this case, the torque of articulation A is expressed in the next formula.

This method is shown in Fig. 4. In this case, the torque of articulation A is expressed in the next formula.

$$M = aF \qquad (1)$$

Where a is the horizontal length between articulation A and foot, and F is a force depending on the weight of the body and legs.

This estimation method gives so large a torque that the robot can stand on ice. Motor with a higher torque make the robot heavier and heavier robots demand more higher torque. As a result, we could not select motors by this estimation method.

We therefore developed a new estimation method regarding foot friction. This

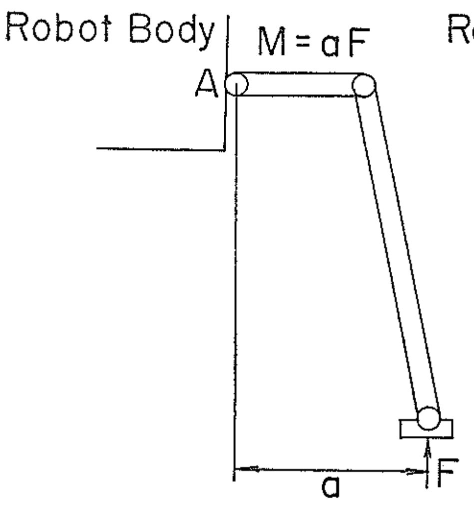


Fig. 4 Articulation torque without consideration of friction

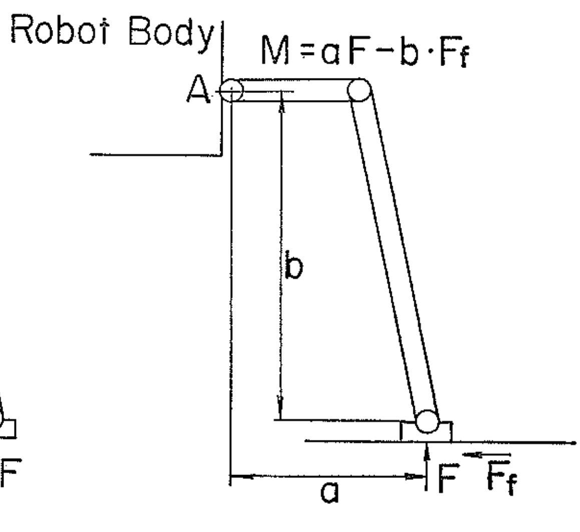


Fig. 5 Articulation torque with consideration of friction

method is shown in Fig. 5.

According to the method, the necessary torque of the articulation is expressed in next formula.

$$M = aF - bF_f \qquad (2)$$

The estimation mentioned above is an example of the estimations of articulation torque. Many estimations of the articulation torque were carried out for various conditions. The estimated torque by new method is so small we can select the motors for the articulations.

3.2 Motor and Control System

The walking robot has eighteen articulations, the rotations of whitch should be controlled with high accuracy. Therefore, motor and control system hardware is as important as control programs.

(1) Motors

The motors of the robot are electric and driven by 70 Volt DC power. Each motor has an encoder that generates 100 pulses per revolution, and harmonic gears with a ratio of 1/160. The two kinds of motors are selected. The motor for the first articulations is 40 watt and the motors for second and third articulation are 70 watt.

(2) Motor Control System

A motor driver is used for each motor. The usage changes the DC motor into a pulse motor that can simply controlled by pulse signals. The motor with the driver can then be controlled by pulses from a computer.

The motor driver have a pulse counter that counts the pluses from a computer and an encoder and the pulses from a computer and the pulses from a encoder have opposite signs. The motor driver moves the motor to keep the counter value at zero, by this operation, the motor is rotated to the position directed by the computer.

The flow chart of the control method is shown in Fig. 6.

(3) Sensors

Three kinds of sensors are used for the robot. There are six touch sensors, two inclination sensors and a compass.

The six touch sensors are installed at the tops of the six legs. These sensors are composed of a case, a sliding shaft, a spring and a limit switch.

A foot is connected to one side of the sliding shaft and a limit switch is installed on the other side. The moving range of the sliding shaft is 3 cm and a spring returns the sliding shoft to back in its initial position. When the shaft is moved 0.5 cm, the limit switch is closed and the computer can recognize that the leg is touching the ground. After the touching, the leg is moved down slowly 2.5 cm by

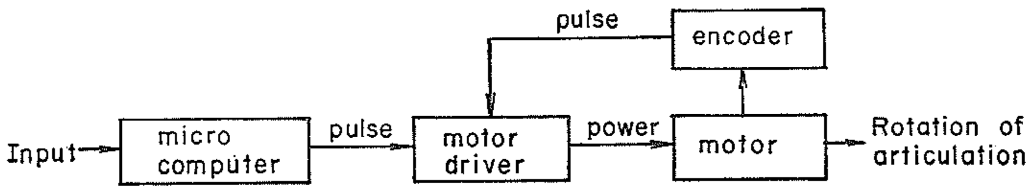


Fig. 6 Control network

the computer. This operation avoids the impact of touching.

The two inclination sensors and the compass are installed on the body. The axis of the two inclination sensor is arranged horizontal and the axis is right-angled. The type of the sensor is pendulum type and the settling time is 1 sec.

The compass is a flux gate that has no movement and that responds quickly. The robot can therefore walk keeping the inclination and direction of body constant by the sensors.

(4) Micro Computer

The robot is controlled by a 16-bit micro computer. The MPU of the computer is 8086. Two kinds of interface board are added, one being a PI/0 board. The computer gives pulses to motor drivers and determines the status of touch sensor through this board. The other an A-D converter board used for the inclination sensor and compass.

3.3 Computer Programs

The structure of the AQUAROBOT control program is shown in Fig. 7. The program consists of operating and walking algorithm programs which are independent each other but which are interfaced by a robot language.

A BASIC compiler and assembler are used to develop the control program.

(1) Robot Operating Program (Robot Language)

This program receives commands from walking algorithm program and produces detailed commands for the motor drivers and sends pulses to the motor drivers according to the detailed commands.

a) Robot Language

The fundamental commands included in the robot language are as follows.

LMOVE (legs move) To move the six feet to the next points. The paths are linear and the motions of all legs are simultaneous with the beginning and the end times of the motions being the same. The next feet points are given in 3-dimensional local coordinates fixed to robot body. The number of input data is 18, with x, y, z coordinate of 6 legs.

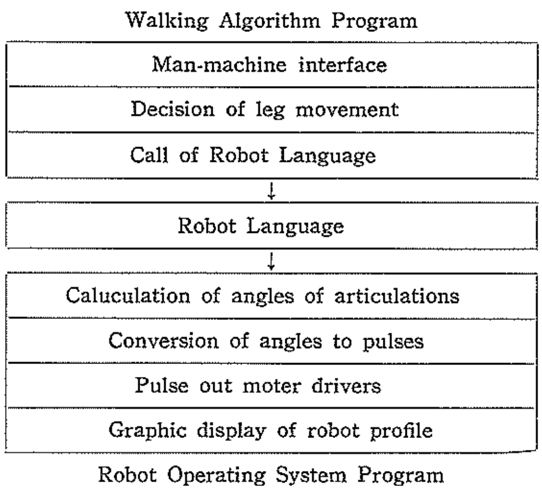


Fig. 7 Structure of the robot control program

LMOVEC (legs move coarse) The function and input data are the same as LMOVE except linear path. Therefore the locus are not always linear but the motions are faster than for LMOVE.

LMOVEX When touch sensor finds the leg touches the ground while moving to the target position, the motion for 2.5 cm farther from that point is added as the stroke of touch sensor mechanism.

LMOVES Similar to LMOVE. The different point is that the motion is stopped when touch sensor senses that the leg has touched the ground.

MOVANG To rotate the indicated articulations by the indicated angles. The number of articulations is 1 to 18.

SPEED To change pulse rate, this command can change the speed of motion of the leg.

While the coordination for the walking motion has cartesian coordinates, the control coordinates of AQUAROBO are rotational coordinate which center on the articulation axis. This is a disadvantage for ease of control because coordinate transformation is necessary. To improve upon this disadvantage, the robot language system mentioned above was introduced. By using this Robot Language the target point of leg can be indicated in cartesian coordinates. This coordinate conversion can be achieved by linear interpolation and synchronization of the motor rotation.

b) Linear Interpolation

A foot must travel along a straight line between two points. This can be achieved, if the interpolated points are made sufficiently and the foot travels from the point to the point.

A Practical method is as follows. At first, the computer calculates the rotating angles of three articulations of the six legs when its feet are on the next interpolated points. Next, the articulations are simultaneously rotated to the calculated angles simultaneously by computer. By repeating the process, the feet travel along the straight line between two points.

This method utilizes linear interpolation by absolute coordinates. In order to reduce the calculating time, the number of interpolated points along the straight line is limited to several points which is necessary to walk.

A Jacobian matrix method was considered as one other method but was not introduced because of the complication of the program.

c) Synchronization of Motor Rotation

When the robot is walking, each leg must move simultaneously, if not, each leg reacts with the others to result excessive motor load and a discontinuous walking motion. Synchronization of motor rotation is therefore necessary. Accurate synchronization can reduce the number of interpolated points mentioned in b).

Generally speaking, when the 6 legs move simultaneously from one interpolated point to next interpolated point, the 18 motors must rotate, reguiring that the computer calculate 18 output pulses. The values of these pulse numbers are different from each other. Therefore, to achieve the simultaneous motion of 6 legs, computer must output pulses to the motor controller with the a speed proportional to these pulse numbers so that the beginning time and the finish time of all articulations are the same.

The synchronization program directly affects the walking speed. We developed a new special algorithm to achieve perfect synchronization only with addition and subtraction of integers of 16 bit numbers, this algorithm is written in assembly

```
10 'SAVE "POUT.BAS",A
20 DEFINT A-Z
30 DIM PULSE(6)
40 CLS
42 '=========================================
45 ' SETING OF PULSES OF SIX ARTICULATIONS
47 '-----------------------------------------
50 PULSE(1)=100
60 PULSE(2)=200
70 PULSE(3)=300
80 PULSE(4)=400
90 PULSE(5)=500
100 PULSE(6)=600
110 '=========================================
115 '        SETING OF SPEED
116 'IF YOU WANT MAXIMUM SPEED, THEN SET SPEED=1
117 '-----------------------------------------
120 SPEED=1
130 '==============================
140 MAX=PULSE(1)
150 FOR I=2 TO 6
160 IF PULSE(I)>MAX THEN MAX=PULSE(I)
170 NEXT I
180 MAX=MAX*SPEED
190 '================================
200 FOR I=1 TO 6
210 TY(I)=PULSE(I)/2
220 NEXT I
230 '================================
240 FOR X=1 TO MAX
250 ALLSTOP=0
260 TOUCHSENSOR$=INKEY$
265 PRINT X,
270 FOR I=1 TO 6
280 IF PULSE(I)=0 THEN ALLSTOP=ALLSTOP+1:GOTO 330
290 IF CHR$(&H30+I)=TOUCHSENSOR$ THEN PULSE(I)=0
300 TY(I)=TY(I)+PULSE(I)
310 IF TY(I)>=MAX THEN OUTPULSE(I)=OUTPULSE(I)+1 :TY(I)=TY(I)-MAX
320 PSET (X,OUTPULSE(I)):PRINT OUTPULSE(I);
330 NEXT I
335 PRINT
340 IF ALLSTOP=6 THEN 360
350 NEXT X
360 '=============================================
370 PRINT "ARTICULATIONE NO.","NUMBER OF PULSES"
380 FOR I=1 TO 6
390 PRINT I,OUTPULSE(I)
400 NEXT I
410 END
```

Pogram 1 Synchronization program

language.

Program 1 shows the algorithm written in BASIC language for explanation. In the program, all variables are integers and division and multiplication are not used.

The pulse output process of the algorithm can be shown by drawing lines on a CRT. On the CRT, the X axis is time and the Y axis is the number of output pulses, and the process draws different inclined lines with inclinations proportional to the pulse out rates.

If this program is run, you can see the fronts of six inclined line progress synchronously and recognize the algorithm. Speed changes are achieved by giving a different integer number to the variable SPEED. The numerical keys from 1 to 6 are assigned to the touch sensor and if any one key is pushed, the progress of the line for that key is stopped instantly.

d) Graphic Display and Simulator Function

This system shows the robot profile by graphic image on a CRT and shows the location and direction of robot by numbers at every step of leg motions. This is shown in Photo 3. A operator on board can recognize how robot is in the water.

Even if the robot is not connected to the computer, the system run independently. This function can be used as simulator of robot motions. This system also checks whether the usage of the robot language is correct. Both the simulator and the checking functions are used as the debug tool for the development of walking algorithm program.

(2) Robot Walking Algorithm

The main purpose of this program is to understand commands from a human operator and to calculate the coordinate values of the points of the leg ends (PTP) to execute these commands.

a) Walking Algorithm

The fundamental concept of the walking algorithm is as follows.

Let us name the every two legs set A and other legs set B. Suppose that the legs of set A touch the ground and the legs of set B do not touch the ground and that the coordinate values of the legs of set A are (X_1, Y_1, Z_1) (X_2, Y_2, Z_2) (X_2, Y_3, Z_3) respectively in the coordinates fixed to robot body. When you substitute next coordinate values of the legs of set A (X_1+dx, Y_1+dy, Z_1) (X_2+dx, Y_2+dy, Z_2) (X_3+dx, Y_3+dy, Z_3) respectively and call the LMOVE command mentioned above,

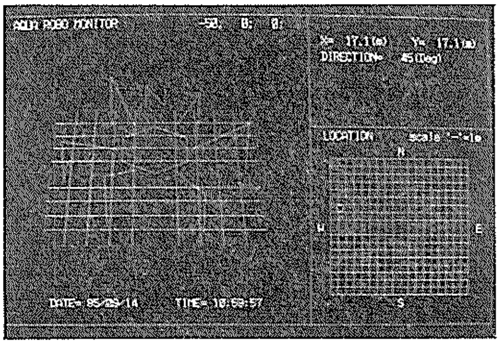


Photo 3 Graphic display of robot motions

causing the robot body to move dx in the x-axis direction, and dy in the y-axis direction without rotation.

Changing sets with same operation makes the robot travel along a straight line with the body height constant. So that it walks straight. Rotating on the spot is similar operation.

The algorithms to walk straight and rotate on the spot are shown in Fig. 8 and Fig. 9 respectively. In Fig. 8 and Fig. 9, the motions 1 to 2 and 2 to 3 are separated for explanation, but are simultaneous in the actual walking operation.

Figure 10 shows how to walk on irregular terrain. AQUAROBOT can walk on irregular terrain with the body kept horizontal at a constant level by stopping the lowering of the legs when they touch the terrain surface, according to the information from touch sensors.

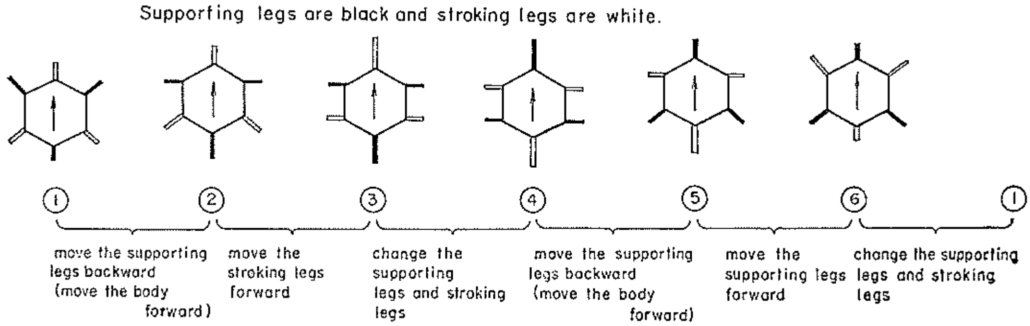


Fig. 8 Algorithm to walk straight

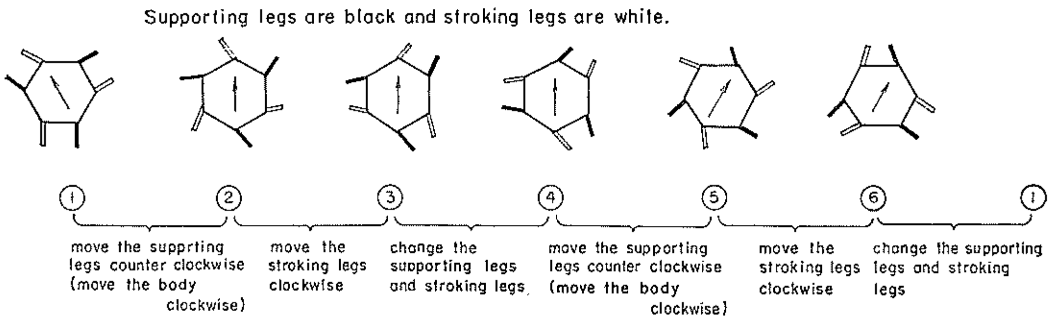


Fig. 9 Algorithm to rotate on the spot

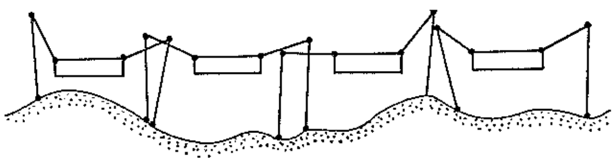


Fig. 10 How to walk on irregular terrain

b) Walking Pattern

The algorithm described above is for the standard 3 legs walking pattern. AQUAROBOT has several walking patterns varying the numbers of stroking legs and the supporting legs as follows. Software control system enables these many walking patterns.

- 3 stroking legs and 3 supporting legs

This is standard walking pattern. This walking speed is the fastest of all the patterns.

- 2 stroke legs and 4 supporting legs

As more than 4 legs are supporting the robot body, the payload and stability are larger than the standard pattern. This pattern is the equivalent to that of 8-legged walking robot.

- 1 stroking leg and 5 supporting legs

As more than 5 legs are supporting the robot body, the payload and stability are largest but the walking speed is slow.

- 1 stroking leg and 4 supporting legs

AQUAROBOT can walk with 5 legs, with the remaining one leg used as a manipulator to hold measuring sensors i.e., a leg can be used as an arm with 3 articulations.

- 1 stroking leg and 3 supporting legs

AQUAROBOT can also walk with only 4 legs. Four is the minimum number of legs for walking while statically balanced. AQUAROBOT can continue walking in this mode even if 1 or 2 legs are out of order.

c) Walking Function

The irregular terrain walking program has several functions as follows.

- Terrain profile measuring function

All the motions of the legs are controlled by computer, enabling every position of the legs to be known. The terrain profile can be measured from the locus of the feet while walking on irregular terrain. Photo 4 shows walking on the floor with wooden pieces and Photo 5 shows an example of the locus of the feet. This is one of the most important advantages of the walking robot as it can not only move, but also measure by its legs.

- Motion area expanding function

Generally speaking, a foot must move upward, forward, downward, backward,

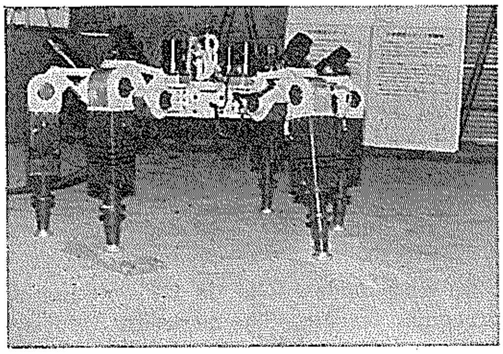


Photo 4 Walking on the floor with wooden pieces

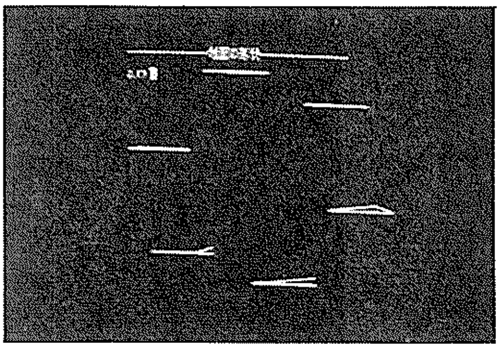


Photo 5 Display of locus of feet

in order, and along straight lines. The locus of a foot forms a rectangle. The motion area of a foot of articurated leg is, however, a space covered by spherical or cylindrical planes. There are number of rectangles in this space. Before walking, one rectangle is selected and a foot can not move outside of the rectangle when in the conventional control method.

Using this function, the control program does not select one rectangle before walking. Instead, the path of a foot is determined according to the positions of the feet of supporting legs.

The motion area of a foot is expanded to maximum area where a foot can move with the next motion.

- Walking parameter assumption function

The walking parameters such as step height and body height can be automatically determined by the control program. Where the inclination of the terrain is changing such as in the case of places between horizontal planes and slopes, walking at high efficiency requires suitable walking parameters. This function assumes the most suitable walking parameters for the terrain condition which is obtained by the terrain profile measuring function mentioned above. This is a sort of artificial intelligence.

- Body inclination control function

Generally speaking, a walking robot walks with the body kept horizontal. If the body is inclined by a slip of the feet or distortion of the terrain, then the inclination must be compensated. The difficult point of compensation is that all the positions of supporting legs must be kept relatively constant during the operation.

At first, we used a simple algorithm to calculate the 2 inclinations of the x-axis and y-axis separately and to add the motion of compensation, but there was the problem that errors could not be ignored because of the feet sliding.

We then introduce a strict solution of the direction and quantity of body inclination from 2 inclinometers installed on the x-axis and y-axis on the body, to transform the control coordinates to the direction of maximum inclination, and solve the problem.

- Body inclination changing function

The body of AQUAROBOT can be kept at any inclination by this function. When AQUAROBOT is walking on an inclined terrain with the body kept horizontal, the feet might touch the terrain surface. In these cases, the body must be kept inclined to same direction of terrain inclination. This function is easily realized because the control program includes a coordinate transformation subprogram for cartesian coordinates, and which does not add more complexity to the calculation.

- Landing point changing function

When a foot can not touch the terrain surface even the leg is lowered completely, the walking program considers that landing at that point is impossible, and automatically changes the landing point. By using this function, AQUAROBOT does not get its legs stuck in grooves or holes.

d) Operation mode

AQUAROBOT has several operation modes as follows.

- Walking mode

The walking mode includes 2 types of walking modes. One is for walking on flat terrain and the other is for walking on irregular terrain. The necessary information to walk straight are the walking direction and the walking distance, while that for rotate on the spot is the rotating angle in each mode. Walking on irregular terrain requires complicated operations but those are processed by artificial intelligence using the techniques of intelligent mobile robot. Therefore, the operational difficulty for the human operator is the same. The step length and step height can be selected freely within mchanical limitations.

The flat terrain walking mode includes a function to walk on the terrain of which profile is previously known to the control computer. In this mode, AQUAROBOT moves its legs according to the "map" created from terrain profile information which is previously given to the control computer.

- Height and width change mode

The height and width of AQUAROBOT can be changed in this mode. When the roughness of the terrain is greater, the height should be taller as shown in Photo 6 so that the feet can be raised higher. When the speed of water current is fast in the sea, the height should be shorter to make the center of gravity lower, while the width should be wider to make it more stable by spreading the legs as shown in Photo 7.

- slim mode

AQUAROBOT can fold its legs to make its width one half of that of standard posture to assume the slim posture shown in Photo 8. It can walk in this slim posture but the walking direction is limited to side ways like a crab. If there are

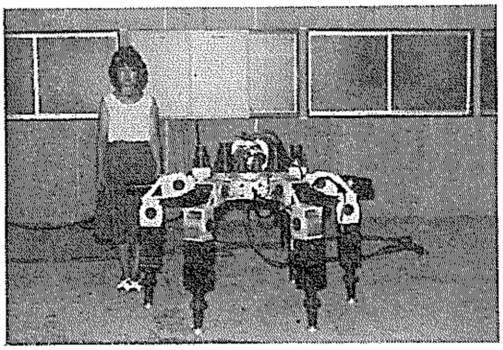


Photo 6 Tall posture

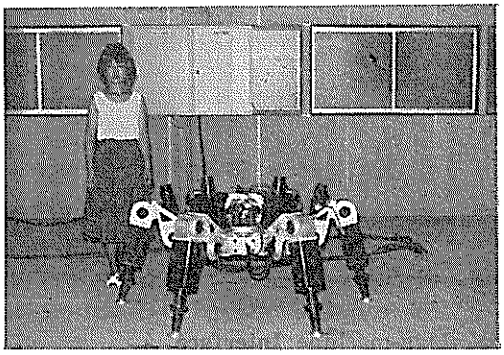


Photo 7 Low posture

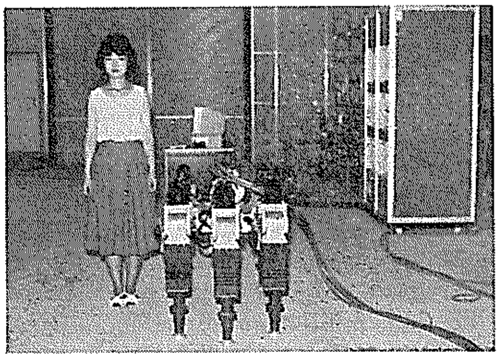


Photo 8 Slim posture

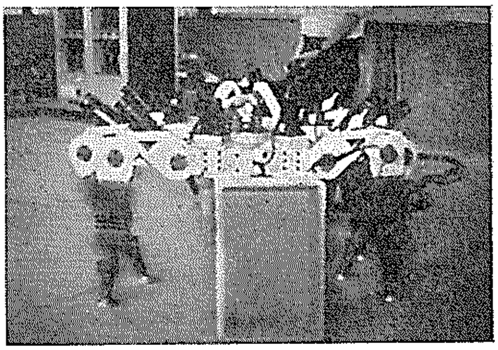


Photo 9 Walking through the obstacles

obstacles in front of AQUAROBOT, it can walk through them by assuming this posture, as shown in Photo 9.

• Initialization mode

AQUAROBOT spreads its legs and removes the support automatically to assume the standard posture from the storage posture in this mode at the beginning of operation. As the encoders of the DC servo motors are of the incremental type, AQUAROBOT must have a constant posture when the control program starts to work. The support for storage is also used to set the initial position of AQUAROBOT.

• Storage mode

As no break is equipped with the articulations, AQUAROBOT must be supported when no electricity is supplied. AQUAROBOT rides on the support and fold its legs automatically to assume the storage posture from the standard posture in this mode at the end of operation. The storage posture has the least bulk, as shown in Photo 10.

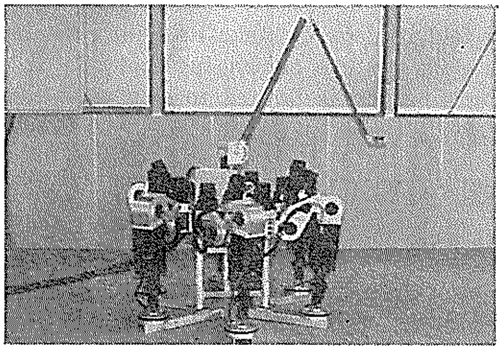


Photo 10 Storage posture

• Speed change mode

The rotating rate of articulations is altered in this mode.

e) Man-machine Interface

The control program uses a conversational system and the operator simply selects an operation mode from the main menu and responds to the questions from the program. The necessary information for walking is generated by the program automatically in real time.

3.4 Walking Test and Its Result

(1) On Flat Terrain

As the first stage, the walking test using the flat terrain walking program was carried out on the concrete floor of the laboratory. This program was developed so as to inspect the fundamental performance of the experimental model. This program does not use outside sensor information such as touch sensors, inclinometers and a solid state flux gate compass but only inside sensor information such as the encoders of actuators. Therefore, using this program, AQUAROBOT can know its relative posture but can not determine the absolute position or direction. AQUAROBOT can walk with this flat terrain walking program on the flat terrain or on terrain for which the profile is previously known to the program.

The experimental model can be operated on the flat floor with every walking pattern and every operation mode mentioned in 3.3.

The experimental model can also walk over a stair of 10 cm height with the body kept horizontal at the constant level, shown in Photo 11, and can avoid stepping on the edge of the stair by changing the step height and the length according to the "map" generated from information of the stair height and stair position previously input to the control computer.

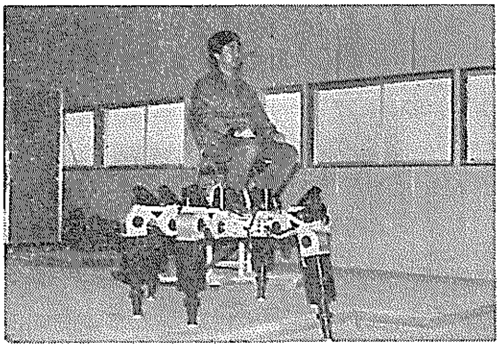


Photo 11 Walking over a stair with one person on the body

The maximum walking speed is about 7.5 m/min., and the maximum rotating rate is 445 degree/min. on flat terrain.

The experimental model can walk with one person on the body as shown in Photo 11. This means that the payload is over 70 kgf. There seems to be more room for payload from the observation of current meters of servo motors, but the maximum payload was not measured because of the fear of damaging the robot mechanism.

(2) On Irregular Terrain

A walking test using the irregular terrain walking program was carried out on a rubble mound. This program is developed for walking on irregular terrain by adjusting the leg motion by using sensor information feedback. It can compensate for errors due to slip of the feet, or distortion of the terrain.

The rubble mound for the walking test was constructed with real rubble for port construction by the divers who are actually working in Tokyo Bay area. The weight of the rubble used is distributed from 10 kgf to 200 kgf. The roughness of horizontal plane is ±5 cm as a completed mound (which is same as actual one), and ±15 cm as a mound under construction (which is one half of actual one) because the leg length of the experimental model is one half of the practical one. The inclination of the slope is 4:1.

Feet are replaced by new type shown in Photo 12 which is suitable for walking on rubble mound. The diameter of a foot is 25 cm and the sole is covered by flat rubber. These feet was developed by the District Port Construction Bureau at Yokohama as the result of real size experiment on rubble mounds constructed on land.

The experimental model can walk on both horizontal planes and slopes as shown in Photo 13 and Photo 14 respectively. The maximum walking speed is 1.7 m/min.

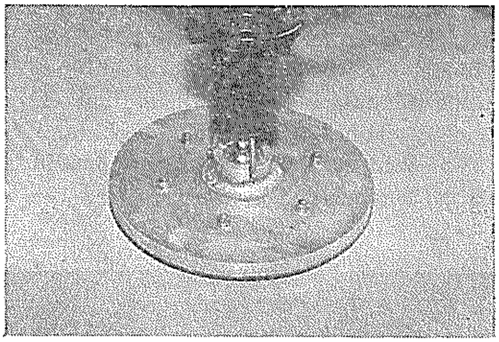


Photo 12 Foot for rubble mound

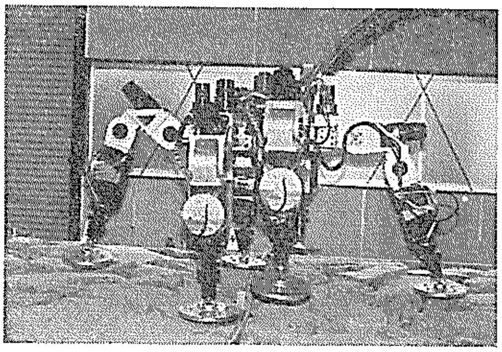


Photo 13 Walking on the horizontal plane of rubble mound

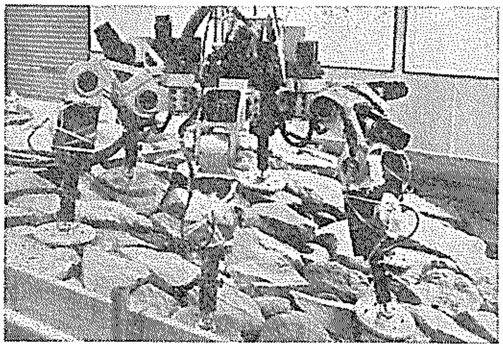


Photo 14 Walking on the slope of rubble mound

on the horizontal plane.

When walking on the slope, the body inclination changing function and the walking parameter assumption function were found effective. Without the body inclination changing function, there was difficulty in walking up the slope because the feet of stroking legs touched the terrain surface. The time taken to walk up the slope was reduced from 30 min. to 10 min. with the use of walking parameter assumption function.

(3) Durability

The experimental model had been displayed at Expo. '87 Tohoku in Sendai from 18th Jul. to 28th Sept., 1987. The walking demonstration of each walking pattern and each operation mode with flat terrain walking program and that with irregular terrain program on the schematic model of rubble mound were shown several times a day. There was some trouble, but the number of days when the experimental model could not make any demonstration for the whole day was only 2. The reason for this accident was the breakage of connecting cable between the articulations and robot body. This was fixed by replacing the cable, and did not cause serious mechanical disorder.

The ratio of the inoperable time was 8.4% for over the whole period. Taking it into consideration that the experimental model had been used for walking test over 2 years before the Exposition, it is proved that the experimental model has excellent durability.

4. Prototype Model for Underwater Test

4.1 Structure and Design

In 1986, we manufactured one watertight designed leg of actual size shown in Photo 15. The structure of the articulations is the same as those of the experimental model and the axes are sealed with o-rings and other sealing parts. This leg was tested in a test tank pressured to the equivalent of a depth of 50 m, to investigate the watertightness, the hydraulic force, and the motional characters. It was found to have sufficient performance.

The prototype model for the underwater test shown in Photo 16, was manufactured in 1987 after consideration of test result of the watertight leg. The main dimensions are shown in Fig. 11 and main features are mentioned in Table 3. The leg length is twice of the experimental model in that a "thigh" is 50 cm and a "shank" is 100 cm. The principal structure of the mechanism and control system are similar to the experimental model.

There are the following differences, however.

The mechanism was designed with o-ring and other sealing parts so that it was watertight.

A manipulator for an underwater TV camera shown in Photo 17 is equipped on the body. This manipulator was manufactured in 1986. It has three articulations of the same structure as legs, except that the first one has a hole at the center through which a tethered cable is connected so as to avoid the tethered cable and the manipulator jamming when the manipulator is rotating.

Non-contact type switches are used as touch sensors to avoid the adverse affects of water pressure changes with increasing water depth. The configuration of the foot is the same as that developed for the walking test on rubble mound by the experimental model.

New type servo drivers and a new layout of devices reduced the volume of the control unit to about one third that of the experimental model although a opto/electric transform device and a interface box are built-in. Photo 18 shows the

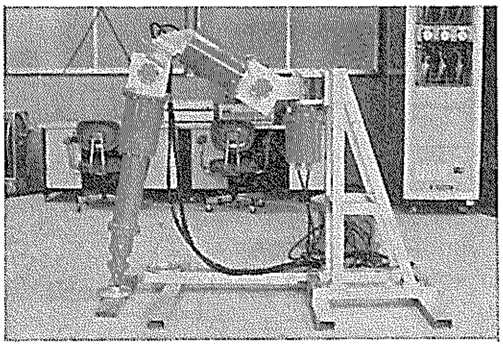


Photo 15 Watertight designed leg

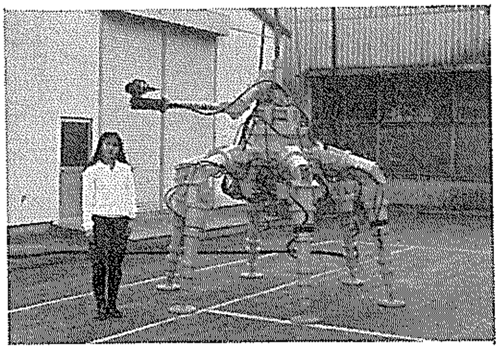


Photo 16 Prototype model

comparison of the control units of the experimental model and the prototype model. This reduction of volume is advantage when the control unit is set on the mother ship.

The control computer is replaced from one using an i8086 microprocessor to one using an i80286. The processing speed is twice that of the experimental model.

4.2 Cable and Control System

An optical fiber link is introduced in the cable system for the transmission of signals to improve S/N ratio and to transmit long way. Several signals of encoders

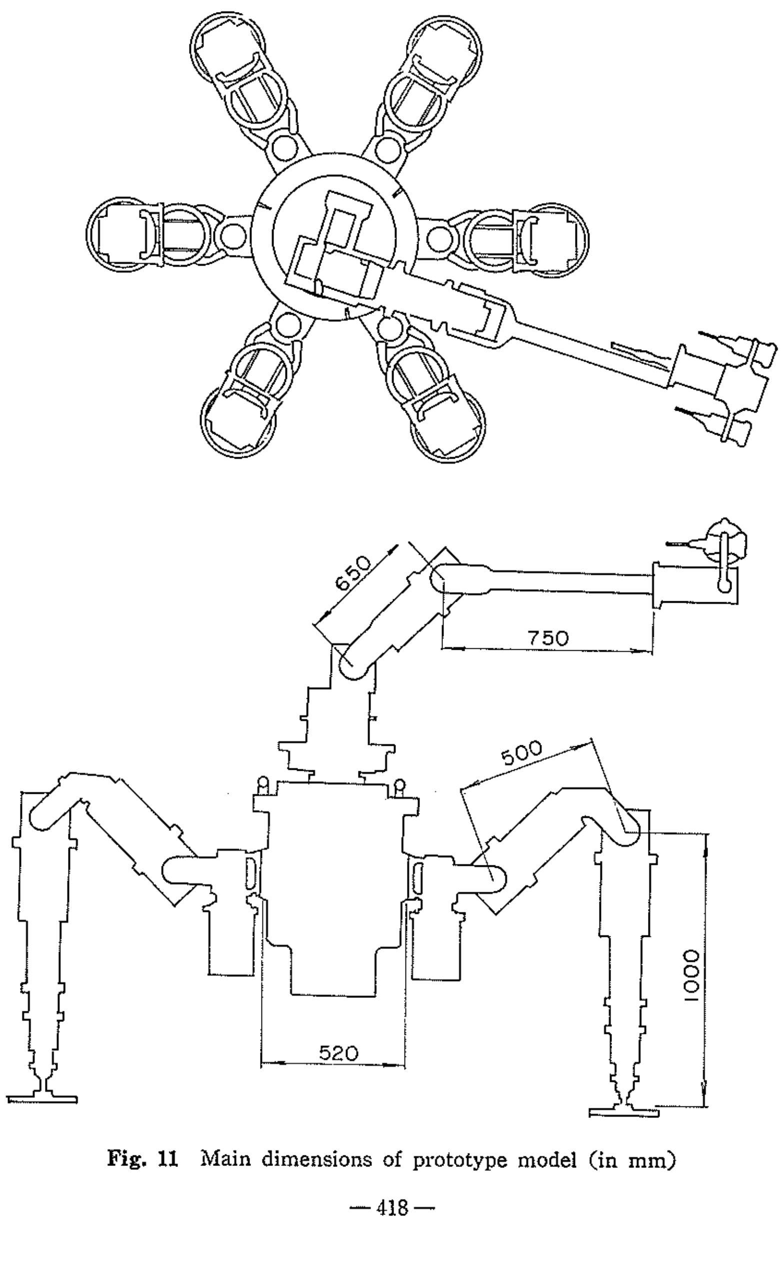


Fig. 11 Main dimensions of prototype model (in mm)

Table 3 Specifications of prototype model

robot type	axis-symmetrical 6-legged insect type walking robot
articulation drive method	semi-direct drive by DC servo motor
control method	software control by micro computer
main material	anti-corrosive aluminum
weight	680kgf (in the air), 380kgf (in the water)
sensors	6 touch sensors, 2 inclinometers, 1 solid state compass, 1 hydraulic pressure sensor
terrain ronghness	±35cm max.
watertightness	50m deep
purpose of practical robot	measurement of flatness of rubble mound supervision of underwater construction work underwater inspection work

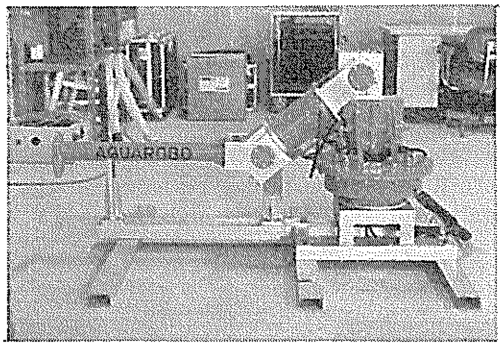


Photo 17 Manipulator for underwater TV camera

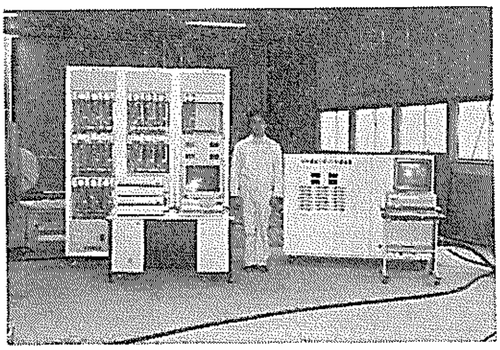


Photo 18 Control units of experimental model (left) and prototype model (right)

are time-shared and transmitted with the one optical fiber. The clock frequency is over 5000 Hz. The visual signal of underwater TV camera is also transmitted by optical fiber.

The tethered cable includes power lines, optical fibers and tension members. The structure of the cable is shown in Photo 19. The diameter is 42 mm and the length is 100 m.

A pair of opto/electric converters are built into the robot body and the control unit accompanied by the use of optical fiber link.

The strength of the tension members is 1500 kgf and the prototype model can be hung by the tethered cable.

4.3 Underwater Walking Test

An underwater walking test was carried out in pure water in a test pool 3 m deep. The overall view is shown in Photo 20 and the prototype model being tested are shown in Photo 21 and Photo 22. The effect of the hydraulic force upon the walking speed and the articulation torque is mainly tested in the test pool.

It seems that the effect of the inertia of robot is larger than the hydraulic force. In the preliminary test, when walking speed exceeds 1.0/min., the effects of inertia have to be considered. These effects can be reduced by the improvement of walking program and adjustment of time constants of the servo system. At less than 1.0 m/min., there are no problems in walking or the operation of the manipulator.

The first field test in the sea was carried out in Dec. 1987 successfully. The prototype model was operated on the underwater rubble mound in the port area of Yokosuka to examine walking performance in the course of actual port construction work shown in Photo 23 and Photo 24.

An underwater TV camera with an ultrasonic ranging device and a newly developed transponder system were fitted to the prototype model in the field test to investigate the performance of total robot system. The underwater TV camera shown in Photo

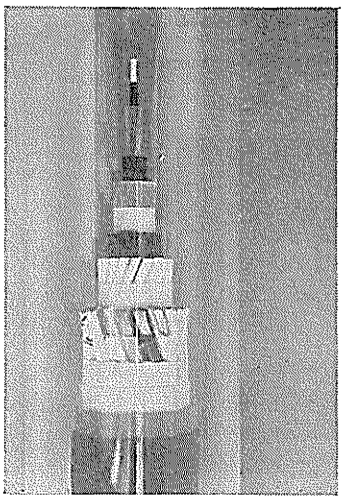


Photo 19 Structure of tethered cable

Photo 20 Overall view of walking test

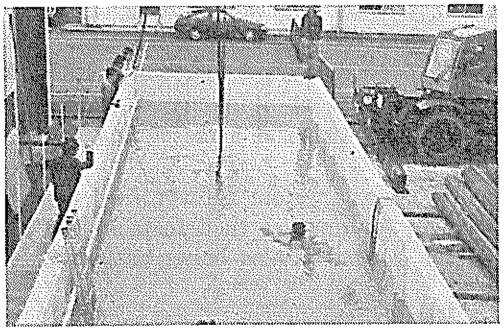


Photo 21 Tested underwater in the test pool

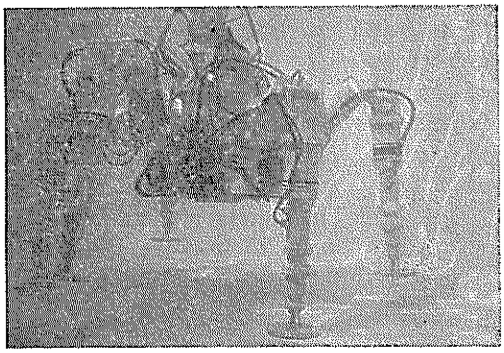


Photo 22 Walking underwater in the test pool

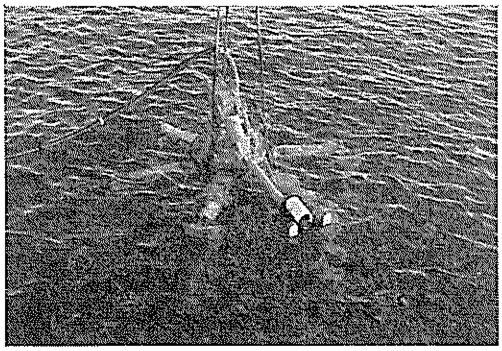


Photo 23 Tested underwater in the sea

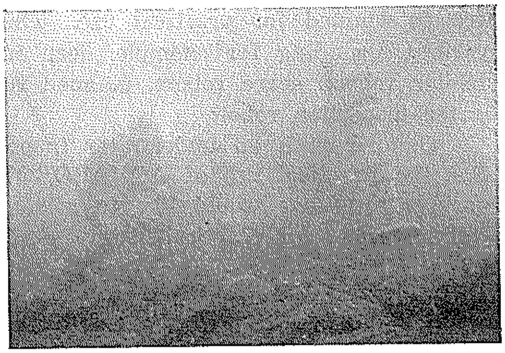


Photo 24 Walking underwater on the sea bottom

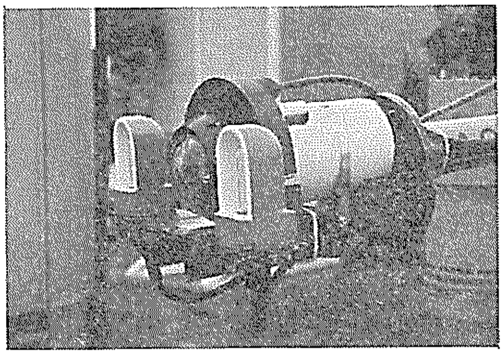


Photo 25 Underwater TV camera with an nltrasonic ranging device

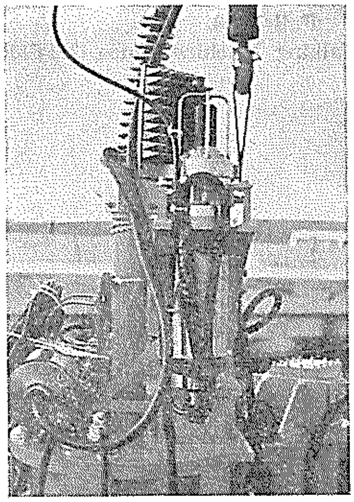


Photo 26 Newly developed transponder system

25 is being developed by the District Port Construction Bureau at Niigata. It can display scales on the screen superimposed with the object and can measure the size of the object by using cursors. The new type transponder system shown in Photo 26 is being developed by District Port Construction Bureau at Shimonoseki to measure the position of AQUAROBOT with an error less than 10 cm at a measuring distance of 300 m.

A cable drum was also manufactured as a support system for the field test.

It is planned to improve the prototype model for another field tests in the sea. A floater to decrease the shock of landing on sea bottom is also being prepared.

5. Concluding Remarks

Research into walking robots is increasing worldwide. The technical level is changing from the laboratory level towards the application level. At the laboratory level, robots were walking only for study, but at the application level, concrete aims are determined for practical use. The application of walking robots are full of variety, including for example, deep sea robots, nuclear plant maintenance robots, soldier robots, space robots, manned vehicles and so on, in addition to our underwater inspection robot.

Our research on underwater inspection robot has been successful up to now. For the practical use of AQUAROBOT, however, there may occur some technical problems and we would like to solve them with every effort to realize the first walking robot for practical use.

(Received on November 13, 1987)

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