The 5th International Symposium on Robotics in Construction June 6-8, 1988 Tokyo, Japan

DEVELOPMENT ON AQUATIC WALKING ROBOT FOR UNDERWATER INSPECTION

Mineo IWASAKI, Jun-ichi AKIZONO, Hidetoshi TAKAHASHI,
Toshihumi UMETANI, Takashi NEMOTO, Osamu ASAKURA and
Kazumasa ASAYAMA*

Machinery Division
Port and Harbour Research Institute Ministry of Transport
1-1, Nagase, Yokosuka, Japan

ABSTRACT

An experimental model and a prototype model were made for development of underwater inspection robot. The experimental model is 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 soft ware of the robots are described herein. The principal features of the models are as follows. The robots are six-legged articulated "insect type" robots known as "AQUAROBOT". Each leg has three articulations and is driven semi-directly by a DC motor that is built in the leg and have a touch sensor on the foot. The robots can walk on uneven ground and can walk in any direction without changing its quarter.

1. INTRODUCTION

Many ROVs (remotely operated vehicles) have been developed but most move while floating in the water. It is difficult for 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 an uneven sea bed without making the water muddy.

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.

The robot is not watertight and the structure and mechanics of legs are not suitable for watertight designs. The technical level for walking robots are far from practical use and there are no real plan of use of the robots. Moreover, there is no underwater walking robot in the world and so We therefore challenged the development of an underwater walking robot to carry out the underwater inspection works.

We developed a experimental model robot in 1985 and a prototype model robot that is made watertight in 1987.

Fig.1 shows the expected work of the underwater inspection robot.

---

*Currently Hitachi, Ltd.

2. STRUCTURE OF THE ROBOTS

The weight of experimental model and prototype model are 280kgf and 700kgf respectively. The difference of weight comes from the watertight design and size. The structures of the robots are almost same.

2.1 body

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

2.2 Legs and Articulations

The legs of walking robots controlled by 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. Therefor, a leg consists of three articulations, or rather, each leg has three degrees of freedom.

Fig.2 shows the leg structure of the robot. The rotating axis of the first articulation that is nearest to the body is vertical and the axis of the other articulations are horizontal. The foot and a leg are linked with a ball joint. A foot has a touch sensor. The length of the thigh and the shank of experimental model are 25cm and 60cm respectively. Those of prototype model are 50cm and 100cm 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(Russell,1983) and TAITAN-3(Hirose et al., 1983) as these robots have link mechanism. There are some differences between the legs and manipulators from the design point of view. It is a 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 the heavy parts like motors must be installed in the legs.

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

2.3 Estimation Method of Articulation Torque

In the first stage, we estimated an articulation torque disregarding the foot friction. This method is shown in **Fig.3**. In this case, the torque of articulation A is expressed in the next formula.

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

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 the heavier robots demand more higher torque. As a result, we could not select motors by the estimation method.

We therefore developed a new estimation method regarding foot friction. This method is shown in **Fig.4** According to the method, the necessary torque of the articulation is expressed in next formula.

$M=aF-bF_f$ ....(2)

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

3. MOTOR AND CONTROL SYSTEM

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

3.1 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.

3.2 Motor Control System

A motor driver is used for each motor. The usage changes the DC motor into a pulse motor that can be 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 pluses 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 and by this operation, the motor is rotated to the position directed by the computer. The motor control system is shown in Fig.5

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

3.4 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/O board. The computer gives pulses to motor drivers and determines the status of touch sensor through this board. The other is A-D converter board used for the inclination sensor and compass.

3.5 Cable

A Cable of the experimental model is consist of many metal wires. An optical fiber link is introduced in the prototype model. The link improves S/N ratio and makes the cable long. The diameter of the cable is 42 mm and the length is 100m. The tensile strength of the cable is 1500kgf. A pair of opt-electric transform devices are built in the robot body and the control box. The prototype model has a large body for the device.

4. ROBOT OPERATING PROGRAM

The structure of the AQUAROBOT control program is shown in **Fig.6**. 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.

The robot operating 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.

4.1 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.

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 3cm 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 AQUAROBOT 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.

4.2 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 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.

4.3 Synchronization of Motor Rotation

When the robot is walking, each leg must move simultaneously, if not, each leg reacts with the others to result in excessive motor load and a discontinuou 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, requiring 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, the computer must output pulses to the motor controller with 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 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.

4.4 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. 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.

5. ROBOT WALKING ALGORITHM

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

5.1 Walking Algorithm

The fundamental concept of 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 (X1,Y1,Z1) (X2,Y2,Z2) (X3,Y3,Z3) respectively in the coordinates fixed to robot body. When you substitute next coordinate values of the legs of set A (X1+dx,Y1+dy,Z1) (X2+dx,Y2+dy,Z2) (X3+dx,Y3+dy,Z3) respectively and call the LMOVE command mentioned above, causing the robot body to moves dx in the x-axis direction, 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.

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

5.2 Walking Function

The irregular terrain walking program has several functions as follows.

a) 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. This is one of the most important advantages of walking robot as it can not only move, but also measure by its legs.

b) Motion area expanding function
Generally speaking, a foot must move upward, forward, downward, backward, in order, and along straight lines. The locus of a foot forms a rectangle. The motion area of a foot of articulated 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 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.

c) Walking parameter presuming 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 plane and slope, 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.

d) 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 2 inclinations of 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 x-axis and y-axis on the body, to transform the control coordinates to the direction of maximum inclination and move.

e) 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 not touch the terrain surface. In these case, the body must be kept inclined to same direction of terrain inclination. This function is easily realized because the control program includes coordinates transformation subprogram for cartesian coordinates, and which does not add more complexity to the calculation.

f) 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 changes landing point. By using this function, AQUAROBOT does not get its legs stuck in grooves or holes.

6. WALKING TEST

6.1 Experimental Model Robot

a) on the 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.

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

The experimental model can walk with one person on the body.

b) on the 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 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 is distributed from 10kgf to 200kgf. The roughness of horizontal plane is +5cm as completed mound (which is same as actual one), and +15cm as a mound under construction (which is one half of actual one) because the leg length of the experimental model is one half of practical one. The inclination of slope is 4:1.

The experimental model can walk on both the horizontal planes and slopes as shown in Photo.1.

The maximum walking speed is 1.7m/min. on the horizontal plane.

When walking on the slope, the body inclination changing function and the walking parameter presuming 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 30min. to 10 min. with the use of walking parameter presuming function.

c) Durability

The experimental model had been displayed at the Expo.'87 in Sendai, Tohoku from 18th Jul. to 28th Sep. in 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 are shown several times a day. There was some troubles, but the number of days when the experimental model could not make any demonstration for the whole day was only 2. The reason of that accident was the breakage of connecting cable between 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.

6.2 Prototype Model Robot

An underwater walking test was carried out in pure water in the test pool 3m deep. The prototype model being tested are shown in Photo.2. The effect of the hydraulic force upon the walking speed and the articulation torque is mainly tested in the test pool. In the preliminary test, walking speed exceeds 1.8m/min.

A field test was carried out in Dec. 1987. The prototype model was operated on the underwater rubble mound in the port area of Yokosuka to examine walking performances in the couse of actual port construction work.

A underwater TV camera with ultrasonic ranging device and a newly developed transponder system were fitted to the prototype model in the field test to investigate the performances of total robot system.

7. CONCLUDING REMARKS

Research into walking robot is increasing world wide. The technical level is changing from the laboratory level toward the application level. At the laboratory level, robots were walking only for study, but at the application level, concrete aim are determined for practical use. The application of walking robot 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 will surely occur plenty of technical problems and we would like to solve them with every effort to realize the first walking robot for practical use.

REFERENCES

1) Hirose,s.,Nose,M.,Kikuti,H.,Umetani,Y.,1983,"Adaptive Gait Control of Duadruped Walking Vehicle",Proc. of the 1st Int'l Symp. of Robotics Research

2) Marvin Russell,Jr ,1983,"ODEX1 the First Functionoid", Unmanned Systems,Vol.2,No.2

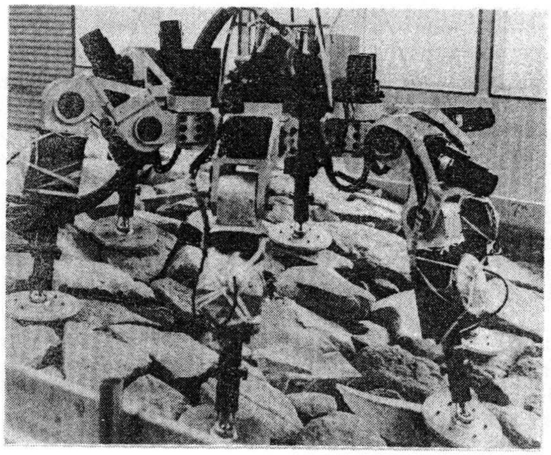


Photo. 1 Walking on the slope of ruble mound

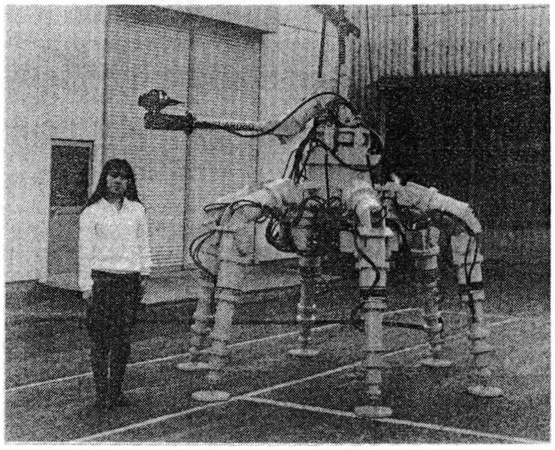
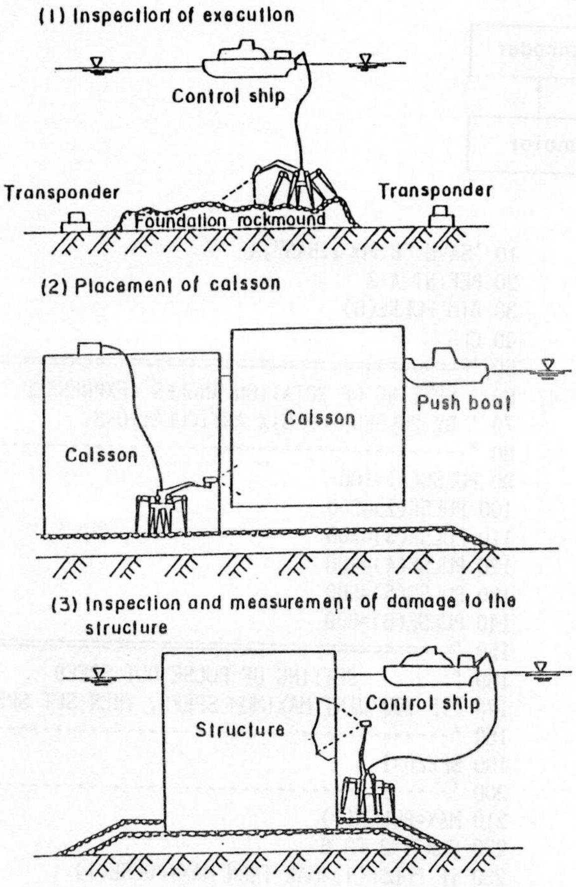


Photo. 2 Prototype model



F ig. 1. Underwatr opertion of the robot

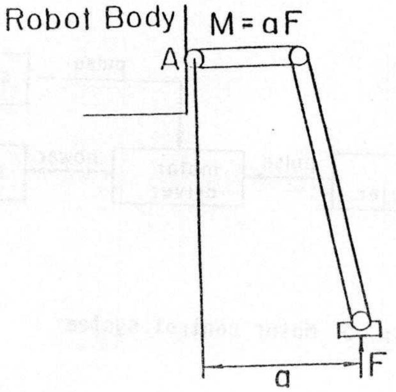


Fig.3. Articulation torque without consideration of friction

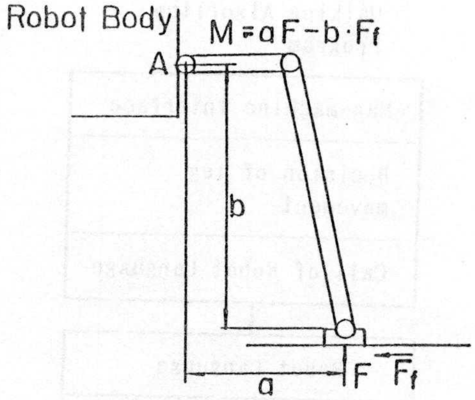


Fig.4. Articulation torque with consideration of friction

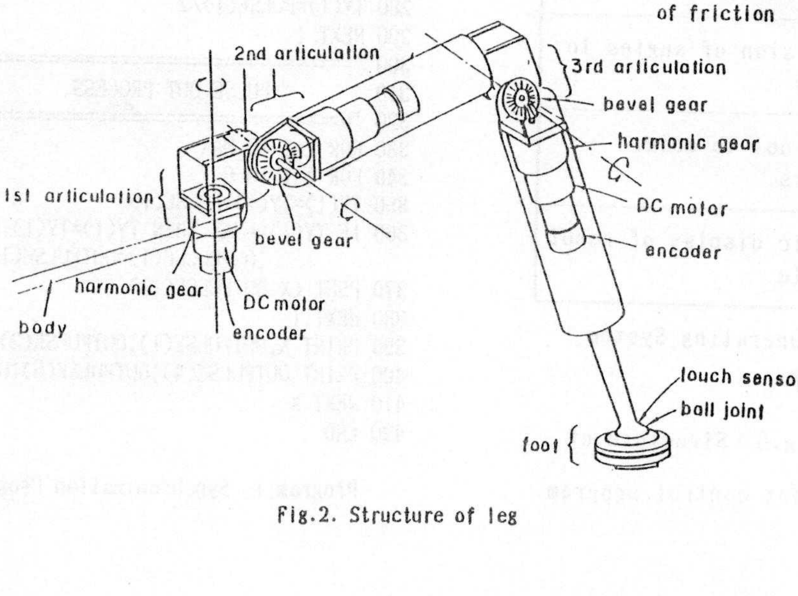


Fig.2. Structure of leg

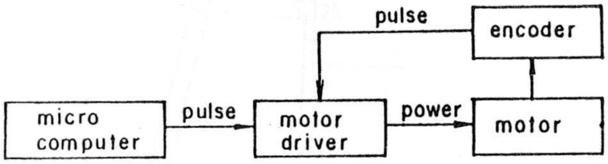


Fig. 5 Motor control system

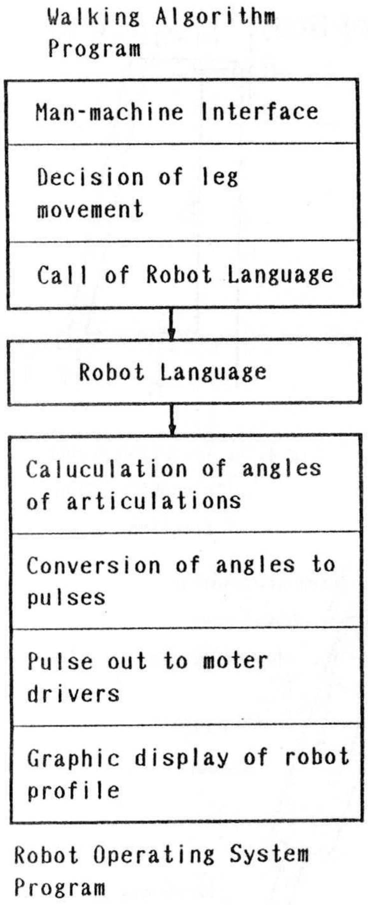


Fig.6 Structure of the robot control program

```
10 'SAVE "B:POU2.BAS",A
20 DEFINT A-Z
30 DIM PULSE(6)
40 CLS
50 '========================================
60 ' SETTING OF ROTATION ANGLES (EXPRESSED
70 ' BY PULSES) OF SIX ARTICULATIONS.
80 '----------------------------------------
90 PULSE(1)=100
100 PULSE(2)=200
110 PULSE(3)=300
120 PULSE(4)=400
130 PULSE(5)=500
140 PULSE(6)=600
150 '========================================
160 '        SETTING OF PULSE OUT SPEED
170 'IF YOU WANT MAXIMUM SPEED, THEN SET SPEED=1
180 '----------------------------------------
190 SPEED=1
200 '----------------------------------------
210 MAX=PULSE(1)
220 FOR I=2 TO 6
230 IF PULSE(I)>MAX THEN MAX=PULSE(I)
240 NEXT I
250 MAX=MAX*SPEED
260 '----------------------------------------
270 FOR I=1 TO 6
280 TY(I)=PULSE(I)/2
290 NEXT I
300 '========================================
310 '       PULSE OUT PROCESS
320 '========================================
330 FOR X=1 TO MAX
340 FOR I=1 TO 6
350 TY(I)=TY(I)+PULSE(I)
360 IF TY(I)>=MAX THEN TY(I)=TY(I)-MAX
            :OUTPULSE(I)=OUTPULSE(I)+1
370 PSET (X,OUTPULSE(I))
380 NEXT I
390 PRINT X,OUTPULSE(1);OUTPULSE(2);OUTPULSE(3);
400 PRINT OUTPULSE(4);OUTPULSE(5);OUTPULSE(6)
410 NEXT X
420 END
```

Program 1 Synchronization Program