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# STUDY OF AN INTELLIGENT HEXAPOD WALKING ROBOT

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## ABSTRACT

A hexapod walking robot has been produced with a view to making use of him in the living and working spaces where there are strong ups and downs like stairs. He is so specially designed as to carry the load always maintaining his horizontal balance. He has eight brains(CPUs) for controlling the movement of twenty driving motors and for detecting his attitude and the environments around him. He can move around himself as well as according to the operator's commands. This paper presents his configuration, structure and mechanism, and intelligence.

## 1 INTRODUCTION

Almost all the land surface area of the earth, including the area inside houses, cannot be traveled through by the moving machines with driving wheels. Many research institutions have been studying the robots [1] which can travel through not only the land surface but also the sea bottom. These moving machines, because they were produced for different objects of development such as for military use and for preventing calamity, were not always used as helpers of men in residential and working spaces. The robots used in such places must have the ability of ascending and descending the stairs, running through an unlevelled ground, and stepping over an obstacle. The legged robots under studying are mainly of two-(bipedal)[2], four-(quadrupedal)[3-5] six-(hexapodal)[6,7] and eight-leg(octopodal)[8] types similarly to animals. In natural, the one needed most intelligent control is of a two-leg type. However, considering the idea that they are used for load carriers, it seems that four- and six-leg types are rich in practicality. In this case, the dynamic walking is difficult because of the problems in structure, weight and energy; therefore, the subject for the present is at achieving the way of static walking.

Some existing robots with more than four legs have the construction so that they can carry loads always maintaining their tops horizontal while ascending the stairs or stepping over an obstacle by shortening and stretching their legs.

However, the type with the retractable legs has the structural defect that he has narrow load-carrying platform because the tops of legs protrude over the platform whenever he shortens his legs. This defect would be improved by employing the articulated legs but new problems arise; the spans among the legs must be broadened lest the legs interfere to each other. Taking these facts into consideration, the principal problem in the legged-robot should be the improvement in leg-structure.

In the present paper, a hexapod walking robot has been manufactured with a view to making use him in the houses and work shops where there are obstacles and stairs. This robot is a hybrid-type one having six legs and wheels. If he is granted a function of only recognizing and studying obstacles and stairs, he can move autonomously. However at the present stage, a satisfactory device for recognition has not yet been developed, and is now being developed as presented [9] in the other pages of this proceedings. He is, at present, remote-controlled and semi-autonomously controlled according to operator's commands transmitted through a key-board with a joy-stick. When the adjustment by observation is not possible, for instance, maintaining his figure horizontally can be autonomously controlled. The software controlling the robot is written in assembler and LSI-C languages. The robot can be manually controlled using a remote-control box and/or semi-autonomously controlled when the environment is known. If the environments such as the height, width and the number of stairs are unknown, the robot can be remotely controlled by an operator.

This paper describes his structure, configuration of controlling circuits, and the methods how he can walk-up the stairs and maintain his attitude.

## 2 ROBOT STRUCTURE

Firstly, the functions and mechanisms of our robot are briefly outlined. This robot is equipped with the ability stated above; namely, it is provided with six legs and six driving wheels and twenty degrees of freedom altogether. In detail, all legs have the functions of raising and lowering the body, and swinging themselves. Besides, the front and rear legs respectively have the functions of running and steering by

wheels.

Figure 1 shows the appearance of the hexapod robot. Hereafter, the right-hand-side legs are referred to as R-legs and the left-hand-side legs as L-legs, and the front, middle, and rear legs as A-, B-, and C-legs successively. For instance, the left-hand-side-rear leg is called LC-leg.

### 2.1 Motors Employed

Each leg, in order to move the body stably under the attitude as free as possible, has H-motor; this is used for swinging the leg in the forward and rearward directions and is installed in the body. The leg has also L-motor for elongating and shortening the leg. Both the H- and L-motors are used in ascending stairs and stepping obstacles over. In addition, the front- and rear-legs respectively have D-motors for driving wheels and S-motors for steering wheels. D-motors are used mainly in running on a road or a flat area. As a whole, this robot has 20 DC-motors and 20 degrees of freedom. The number of rotation of each motor is counted by use of a rotary encoder installed near the motor.

The reason why the robot has six legs lies in the functional necessity that the body can be kept balance statically even on the stairs and its top platform can be kept level in order to be used as a load carrier. The length of each leg can be changed by the retractable movement with use of sliding guides and a chain-sprocket mechanism and each leg can be swung round a joint. The fact that each leg has both the functions of retractable and swinging motion serves to minimize the space between legs and to avoid the collision chances among the legs as few as possible. In order to increase its practicality, a peculiar improvement has been made in that the upper part of the leg never protrude over the top body-surface even when the body is lowered to the lowest position.

The robot body is supported usually by the front and rear legs; thereby, he never falls while the gravity center is situated within them. He runs on the flat road with use of the wheels attached to the feet of A- and C-legs.

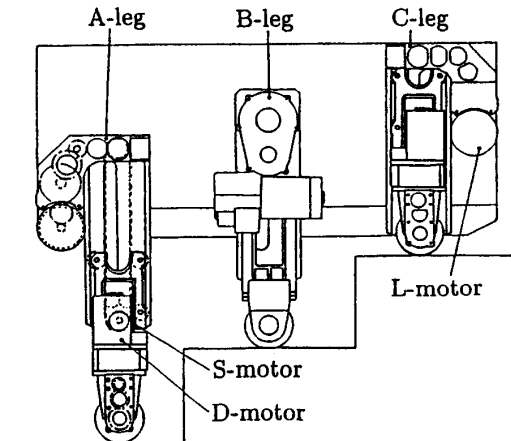


Fig.1 Appearance of the hexapod robot

### 2.2 Leg Structure and Characteristics

Figure 2 and 3 show the details of the leg- and foot-structure which award four functions to the legs; namely, elongating and shortening, swinging, running, and steering the body.

As mentioned earlier, the retractable legs have the defect that the load-carrying platform should inevitably be made narrow and the articulated legs have the defect that the moving region of the legs is restricted. In order to avoid these structural problems the present hexapod robot is improved in that the legs have both the sliding and swinging structure.

The leg is consisted mainly of a first leg, a second leg, and a wheel part called a foot in this paper. A leg base in Fig.2

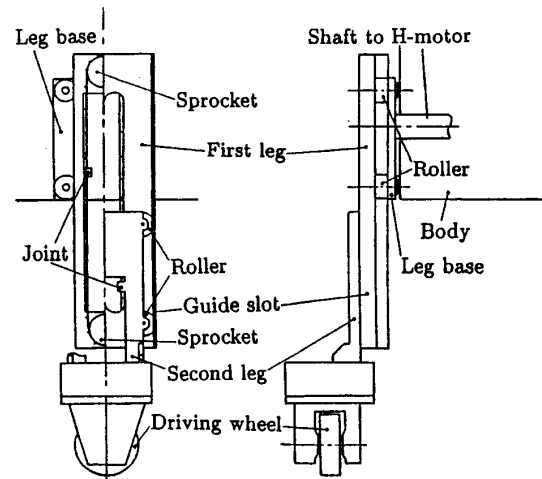


Fig.2 Structure of legs which enable length variation and swinging motion

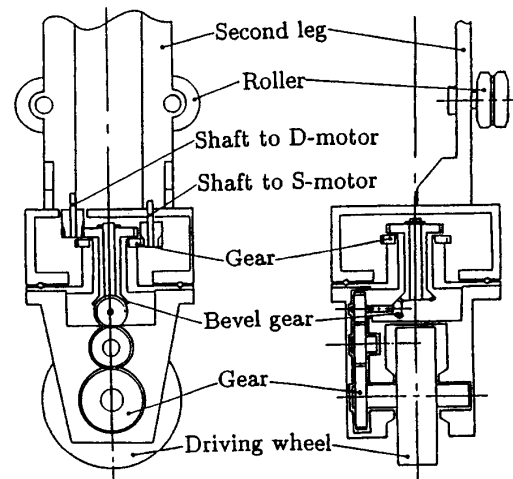


Fig.3 Foot structure for steering the legs and for running with wheels

is connected to H-motor mounted in the robot body via a driving shaft. Four rollers are arranged on the leg base and are fitted in the outside slide guides of the first leg. There are also inside slide guides in the first leg, where the second leg slides with the help of four rollers arranged on the second leg. At the lower end of the second leg, the wheel assembly is installed, the details of which is shown in Fig.3. At the both sides of the first leg, two photo-interrupters are mounted; thereby detecting the upper and lower limits of the leg movement.

The whole legs can be swung by rotating the leg base; therefore, by way of the rotation of H-motor. A chain- and two-sprocket mechanism is so arranged that both the first and second legs can slide to each other in the following way: One point of the chain is fixed by a joint to the middle part of the second leg, the other point is fixed by a joint to the leg base, and two sprocket are positioned on the center axis of the first leg. The upper sprocket is connected to the shaft of L-motor via the series of gears, whose appearance is shown in Fig.1. Consequently, the rotation of the upper sprocket in the right-hand-side direction causes to bring down both the first and second legs; inversely, the rotation in the left-hand-side direction makes both slide toward upper direction. Of course, shortening the legs results in lowering the robot body and elongating the legs results in lifting the body.

Thus, the feature of the structure lies in the fact that the long moving distance, which is almost as long as the summation between the first- and the second-leg length, is achieved in spite of the compact size. The length and the position is then detected by the rotary encoders which are connected to L- and H-motors.

The lower part (foot) of the leg in Fig.3 is driven by D- and S-motors. The wheel is driven via a shaft, a pair of bevel-gear, and 3 spur-gears which are connected to D-motor, thereby moving the robot body toward front and rear directions. In the other hand, the wheel box is rotated by S-motor via a shaft and a spur gear, a function which steers the moving direction of the body. There are also two encoders connected respectively to the shafts of D- and S-motors, which instal-

lation serves to control the running speed and its direction (yaw angle).

## 2.3 Specifications

As shown in Tab.1, the robot has the dimensions of 587mm wide, 850mm long, and 370-760mm high, and can run maximally at the speed of 5km/h on the flat road. This has been so designed as to carry the load, the motors used are powerful ones.

The weight of each leg is as follows: The first one of A- and C-leg has the weight of 95.1 N including L-motor and the second one 50.9 N including S- and D-motors. The first one of B-leg has the weight of 100.2 N including L-motor and the second one 24.6 N without motor.

The swinging angle is changeable within 30 deg. toward front and rear directions and steering angle can be altered toward all directions. The average operation speed is as follows: The speed of shortening and elongating the leg is about 100 mm/s, steering speed is 90 deg./s, swinging speed is 120 deg./s. Seeing from the point of mobility, the functional variety of the leg is the feature of this robot; however, this fact resulted into increasing the weight of the other parts such as the motors and the body not only of the legs. We will replace the present leg structure to the lighter one employing a new artificial muscle under development[10].

## 3 CONFIGURATION OF CONTROLLING CIRCUITS

Figure 4 shows the block diagram. Fig.5 shows the flow of the signals among CPUs and the configuration of the CPU-blocks. The controlling circuits consist of , as shown in the figure, six CPU boards which controls respective legs, a remote-CPU board which communicates with the operator's commands and manages the information from various sensors, and a master-CPU board which manages concentrically all the leg-CPU boards. The configuration and the roles of respective CPU blocks are as follows:

### 1. Master CPU block

Master CPU block is the one which controls all the system and gives commands to the leg-controlling CPUs according to the instruction from a remote control CPU. Thereby, all the movements of the legs are managed by the master CPU (V50, 14.7MHz clock).

The master CPU block has the areas of 64-kByte RAM, 2-kByte dual port RAM (DPR) respectively to 6 legs, 128-kByte ROM, and the input-output ports for emergency stop (ES), serial control units (SCU), interrupt control units (ICU), and timer control units (TCU).

### 2. Remote CPU block

The remote CPU (V40, 14.7 MHz) is installed in the remote CPU box, which not only reads the data and commands given by the keys, switches and a joy-stick and transmits them to the master CPU but also receives the commands from the

Tab.1 Specification of the robot

Length	350mm
Width	587mm
Height	370-760
Weight	2000N
Load capacity	200N
Running speed	5km/h
Battery for driving motor	24V,36Ah
for control board	12V,2.2Ah
Motor for swinging	200W,3000rpm
for telescopic motion	200W,3000rpm
for steering	10W,2250rpm
for running	90W,3000rpm

master CPU ( baud rate of 19200 bps ). It also displays the information on a panel of liquid crystal display (LCD, LM044L) of 4 rows by 20 columns and senses the horizontal level of the robot body by communicating with a peripheral port interface (PPI,  $\mu$ PD8255A).

The remote CPU block has 8-kByte RAM, 64-kByte ROM, and peripheral port interfaces (PPI) for LCD display, A/D converter, and for reading the state of switches and inputs to keyboard.

### 3. Leg CPU block

The six leg-CPU blocks are the ones for feed-back controlling the respective motors according to the commands transmitted by serial transmission from the remote CPU. Since it is necessary to communicate mutual information at the highest speed, the data communication between the master-CPU and the leg-CPU is done through dual port RAMs(DPR).

Six legs are controlled by the respective CPU blocks(V40, 14.7 MHz), each of which servo-controls maximally 4 motors according to the instructions from the master-CPU and by reading the data transmitted from the other CPUs.

The leg CPU block has the areas of 64-kByte RAM, 2-kByte DPR each, and 64-kByte ROM, D/A output ports for four motors, and input-output ports similar to those of master-CPU.

### 3.1 Feedback control of motors

The rotation-speed and the rotation number of motors are closed-loop software-servocontrolled. Software makes two-types of PID-feedback control; the one is the position feedback mode by the use of position error, speed and the integration of position error. The other is the speed feed-back mode by the use of speed error, acceleration, and the integration of the speed error. These control is done by generating interrupt and is proceeded merely by giving the goal (the number of pulses) from the software.

Interruption for feed-back control is made within the 20 ms interval by the use of the following equation.

$$V = e\alpha - s\beta + i\gamma \quad (1)$$

where, the notation  $V$  is the output,  $e$  the position error,  $\alpha$  the position coefficient,  $s$  the speed,  $\beta$  the speed coefficient,  $i$  the integral of the position error, and  $\gamma$  the integral coefficient.

Driving the motors is made by the method of a pulse width modulation (PWM), thereby, not only its duty-cycle (the pulse numbers of outputs to D/A converter) but also the pulse amplitude (D/A value) is changed according to the table pre-determined in relation to the difference between the target value and the present location. Then, in order to move smoothly, the moving rate is divided into 41 stages determined experimentally. The rotation direction and quantity are measured with rotary encoders and are servo-controlled by their controlling circuits. The result of Eq.(1) is transmitted to the motor by way of the interval interruption caused every 2 ms.

Figure 6 shows the output signal of D/A converter trans-

mitted to the power amplifier of the D-motor when the robot moves slowly at the speed of 1 m/s. It can be seen that amplitude as well as pulse width (series of 2ms-pulses) are changed. In this record, the components of one- and three-width are observed.

## 4 CONTROLLING SOFTWARES

The softwares controlling each CPU are composed of the monitor program written in an assembler language and the functions written in LSI-C program. They are translated into

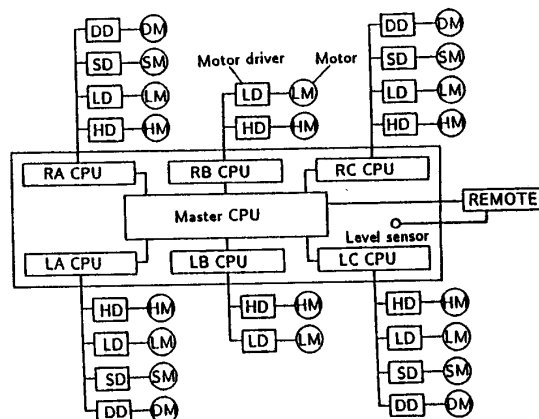


Fig.4 Block diagram of the signals

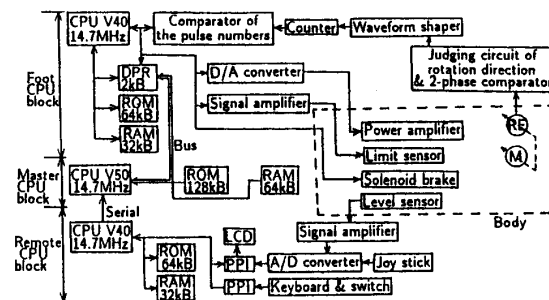


Fig.5 Signal flows

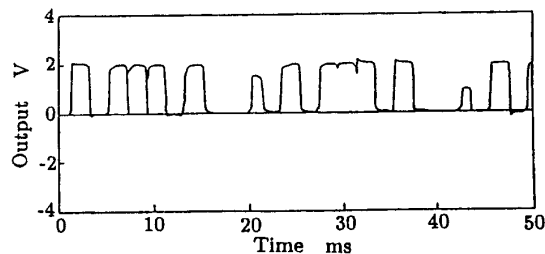


Fig.6 Driving signal of D-motor

machine languages and are re-written into ROMs respectively of the master-, remote-, and leg-CPU with a help of ROM writer.

The task of master program is as follows. Main routine will start promptly after a hardware reset. As soon as the power is supplied, the peripheral ICs are initialized and set into a stand-by state; then an actual processing is started. The main routine displays the following messages and urges the operator to select one of the following modes:

- (1) Manual operation mode.
- (2) Mode of changing the running direction and attitude.
- (3) Mode of passing over obstacles.
- (4) Mode of ascending the stairs.
- (5) Mode of descending the stairs.
- (6) Autonomous mode.

The program of these modes are composed of the functions which carry out the respective tasks. At the present stage of development, the perfect autonomous control has not yet been achieved. However he can walk and run around in the house according to the pre-determined procedure and to the manual control. The principal functions constituting the program are as follows:

- (a) check the state of emergency-stop key and necessary treatment,
- (b) driving motors, and reading the states of motors,
- (c) level adjusting by elongating L-motors of A-, and C-legs after reading the body level,
- (d) giving the target values after entering the position feedback mode,
- (e) giving the target speed after entering the speed feedback mode,
- (f) check the state of motor,
- (g) processing with joy-stick using the interval interrupt of every 100 ms, then the follow-up control is done in such a way that the value is changed gradually even when the joy-tick is altered abruptly,
- (h) manual-switch processing using interval interrupt of 100 ms, then the gradual follow-up control is also done,
- (i) calculating the pulse numbers and speed for elevating and lowering the legs,
- (j) calculating the pulse numbers and speed for steering the S-motors and driving the D-motors,
- (k) detecting the distance to the wall and obstacle.

## 5 METHOD OF WALKING ON THE STAIRS AND STEPPING OVER OBSTACLES

Figure 7 shows the procedure how the robot ascends the stairs of two steps keeping his static balance. The procedure is

1. Running with driving wheels while keeping B-legs usually lifted.
2. When his A-legs reach the front end of the stairs, B-legs are landed.

3. After uplifting A-legs on the up-step, the body is proceeded forward, then the body is lifted lest his front bottom side collides with the steps.
4. B-legs are lifted on the up-step. In order to prevent collision, care is taken in such a way that the frontal end of the body may not protrude more forward than the position of A-legs.
5. To lift A-legs on the next step, B-legs are advanced till they fully approaches A-legs but within the range of no collision, then the body is lifted by elongating B- and C-legs. A-legs are stepped up on the second step.
6. To step C-legs up, B-legs are backed and C-legs are lifted.
7. C-legs are landed on the first step.
8. B-legs are stepped up on the second step. In order to lift C-legs on the second step, the body is advanced paying attention that that the position of the feet of C-legs is kept almost unmoved.
9. C-legs are lifted on the second step.
10. The body is advanced by the driving wheels.

For the stairs having three steps or more, ascending the stairs can be done by repeating the above mentioned procedure. If the height and length of step, and the number of steps are known, the automatic lifting is also possible according to the repeating operation of the software.

## 6 HORIZONTAL BALANCING

Remote control by an operator depending upon his recognition is difficult in such cases when the body of the robot is inclined while the robot is walking-up and -down the stairs

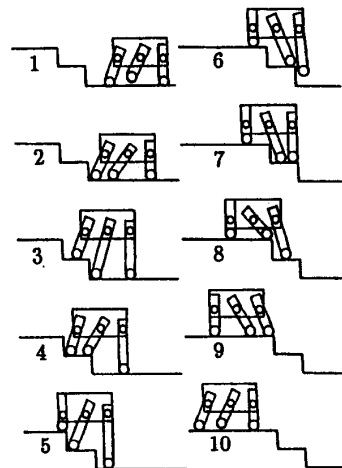


Fig.7 The procedure for walking-up the stairs

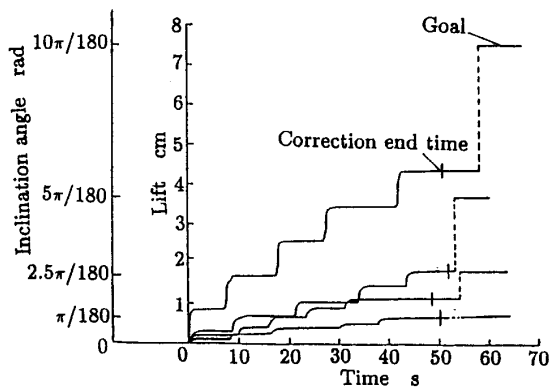


Fig.8 Horizontal balancing

or running on the unlevelled ground. Considering such cases, the robot is so designed as to sense horizontal level and keep his balance autonomously.

The inclined angles are sensed using two level-sensors installed in his body and the quantity for one step correction is determined according to the magnitude of the angle of inclination. The corrections for the forward and backward direction and the right- and left-hand side direction are made by turns by elongating the legs till the pre-determined retry numbers is reached.

Figure 8 shows the time elapse of elongating the LC-legs when the body is unbalanced from the rolling motion. The maximum correction angle per one try has been given as  $2.5\pi/180$ (rad), and the maximum retry number as 5 times. The figure shows the four instances when the inclination angle observed from backward was changed as  $\pi/180$ ,  $2.5\pi/180$ ,  $5\pi/180$ , and  $10\pi/180$ (rad). As can be understood from the figure, the target value; namely, the horizontal state of the body is gradually approached by elongating the L-legs. In the figure, the elongation of only LC-leg is shown; however almost the same elapse was also observed in shortening the LA-leg. In order to avoid the fluctuating movement which may occur when the correction quantity becomes too large, the program is written in such a way that the insufficient correction of about 60 % to the target value is carried out. Speaking from the other point of view, this concept is also because we consider that the robot will be used in the field where there is relatively little ups and downs.

## 7 CONCLUDING REMARKS

In this paper, a hexapod walking robot has been developed. Its structure, configuration of the circuits and programs, controlling method, and the walking procedure on the stairs have been described.

The robot is improved in that the legs have both the sliding and swinging structure and he has the characteristics that the long moving distance is achieved in spite of the compact size. But the heavy weight is the great defect, and we will improve him by using the artificial muscle.

At the present stage, it can not be said that his ability reaches a practical or commercial level and the perfect autonomous control has been achieved; however, he can walk and run around in the house according to the pre-determined procedure and to the manual control.

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