PNEUMATICALLY POWERED ARTIFICIAL LEGS WALKING AUTOMATICALLY UNDER VARIOUS CIRCUMSTANCES

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Summary

Legs as a new kind of locomotion way have excellent adaptability to various circumstances (for example, flat ground, slope, staircase, gutter etc.). There are many kind of legged locomotion. We consider that the biped locomotion machine simulates human being's legs in structure and movement. These artitificial legs are supposed to walk on a flat ground, slopes (up and down), and a staircase (also, up and down). Furthermore it can turn it's direction. This machine has pneumatic artificial muscle and pulse width control is adopted for these muscles. Walking control signals are sent from semiconductor memories.

Introduction

Foreword

Major means of locomotion on land include cars and feet. The car is an excellent mean of transportation in point of moving speed, the capacity of mass transportation, efficiency, and stability. Man's feet are no match for the car in these points but have advantages of their own, specifically in adaptability to environmental change, and the smallness of area occupied by the moving mechanism. These characteristics are most conspicuous with a biped walking machine, which may be used directly as a artificial powered prothesis, or as part of a robot working under indeterminate conditions. In view of its possible applications, the biped walking machine is required to possess at least the following four functions:

(1) Motion in a stabilized manner.
(2) Adaptability to environment.
(3) Adaptability to loads.
(4) Versatility of motion.

History of Waseda Automatic Pedipulators

Various countries have attempted to develop a multi-ped walking machine. Usually, such a walking machine uses half of its legs for support and the other half for moving. Its dynamic stability is good because it has 3 or 4 support legs.

Our laboratory has already developed a few biped walking machines, which will be introduced in the following pages.

WAP - 1 (Waseda Automatic Pedipulator-1) /1/

This machine (Fig. 1) was developed in 1969. The WAP-1 uses artificial rubber muscles which are similar to man's muscles in characteristics /2/. Therefore, the artificial muscles are arranged in a way as shown in Figure 1. The feet are]-shaped, so that when the machine is supported on a single foot it may be mechanically stabilized in the sidewise directions. When its walking motion was controlled by manual operation, it walked in a very unreliable manner but it did walk in three ways.

WAP - 2

The WAP-2 was developed in 1970 with the aim of increasing the functions of the WAP - 1 and achieving automatic control of walking operations. The artificial muscles of the WAP - 1 did not

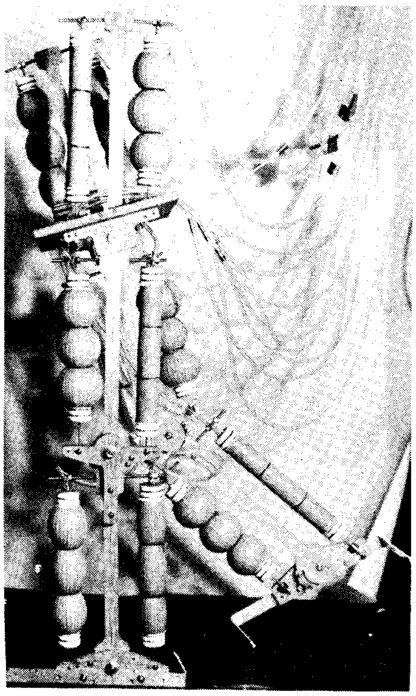


Fig. 1. WAP-1

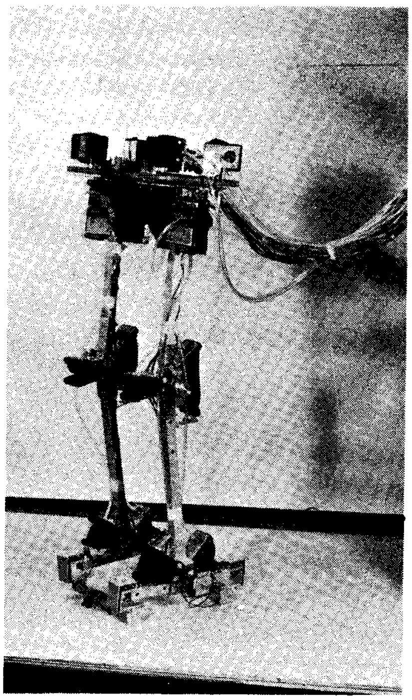


Fig. 2. WAP-2

contract enough for a walking machine,and therefore we developed a rotary type artificial muscle as shown in Figure 2.

In addition, a pressure sensor was attached to the bottom of the feet as a way to accomplish centroid control using feedback signals, With a state detector for determining the present state of the machine, we attempted sequential control so the machine would respond to our sequential steps of control, but no satisfactory results were obtained due to a faulty walking sequence.

Elements of the Walking Machine WAP - 3

Artificial muscle -

The artificial muscle of the WAP - 3 consists of two wooden boards covered with cloth and a rubber pouch sandwiched between the boards (Fig. 3). Air is fed into the rubber poach to produce

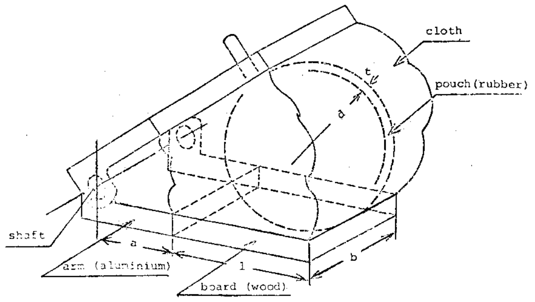


Fig. 3. Artificial muscle

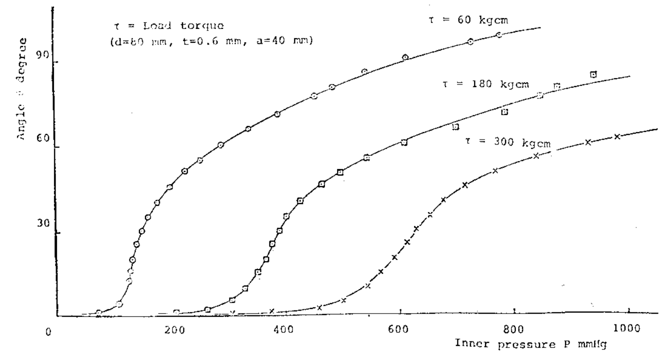
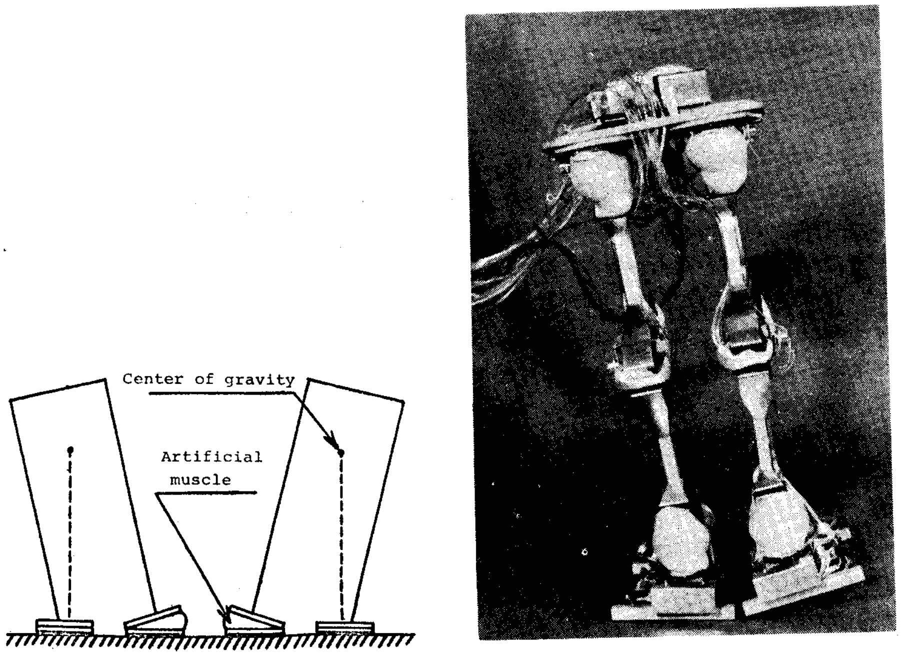


Fig. 4. P ∿ θ curve

a desired angle of rotation and torque. An example of the characteristics of this artificial muscle is shown in Figure 4. Of the various artificial muscles, the one which has a small load variation (do/dt) and a large angle of rotation was selected for use in our walking machine.

Skeleton

A walking motion comprises a movement forward and a sidewise swing. Therefore, a walking machine must have a mechanism which will allow its center of gravity to move to the left and right. The WAP - 3 is fitted with a pouch type artificial muscle on the bottom of the feet as shown in Figure 5. When the artificial muscle on the bottom of the feet is expanded, the center of gravity will shift to the oposite side as shown in Figure 5 (a) and (b). An appropriate amount of air is fed into the artificial muscle on the moving foot when the center of gravity is being shifted. The artificial muscle is deflated gradually when the mechanism is inclined to the right or left. In this way, the artificial muscle on the moving foot serves as a damper and helps to smooth the shifting of the center of gravity.



(a) (b) (c)

Fig. 5. The control mechanism of the center of gravity

The hip joint was designed to have two degrees of freedom; and the knee and ankle joints one degree of freedom. In assembling the mechanism, care was exercised so that the joints will not loose. The bones connecting these joints were square pipes of aluminium alloy. All joints were designed and manufactured to have a joint flexion angle of 90°. The flexion angle of 90° allows the mechanism to climb steps 10 cm high.

Man's hip joint has multi-degrees of freedom and this is combined with the proper arrangement of muscles and their control to permit man to move forward or change the direction of his walk. But it is difficult to make a mechanical model having joints of the same construction. Accordingly, we designed the hip joint of the walking machine to have the capability of flexion forward or backward and the capability of turning around. When the machine is required to change the direction of walking, its hip joint and thigh are turned together. To make the construction simple, we limited the angle of rotation in a single action to 30°.

A biped walking machine must be so controlled that, when it is standing on one foot, its center of gravity will fall within the area occupied by the supporting foot. Thus it is necessary to detect the position of the center of gravity. If pressure sensors are attached to the front and rear ends of the bottom of the feet to detect reaction from the ground, it is possible to determine the position of the center of gravity from the difference in pressure between them. The WAP - 3 is so controlled that the difference will be zero. The strain of the pressure sensor (Fig. 6) is detected by a semi-conductor strain gage, and the ground reaction can be obtained from its reading.

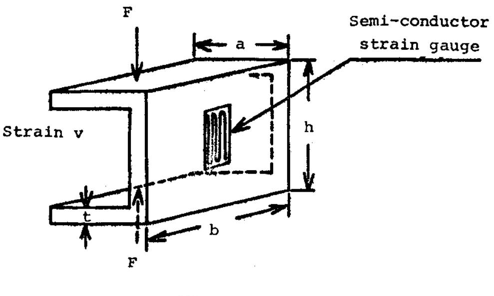


Fig. 6.] - shaped sensor

Control of the Walking Machine

Software of the Control System

Walking action by two feet is a continuous action, so a device emitting such a command signal that will induce the same pattern as man´s biped walking would be most convenient. Since there is no such device available at present, a different control method must be considered. Continuous walking action is divided into parts, which are represented by characteristic phases. Walking action can be approximated by a sequence of these phases. This control method is practicable only when a walking machine walks slowly because no system dynamics is taken into consideration. As a device for producing sequence commands, a programmable semi-conductor memory may be used.

Outline of the Control Device

The control functions that are necessary for making a practical biped walking machine include the following three: One is the capability of changing the bending angle of each joint. Another is the capability of controlling the center of gravity (or the posture). The last is the capability of controlling these two systems, giving commands for walking motion and monitoring it. The last function is upper level. All of them form the hierarchical control system.

The block diagram of the control system is shown in Figure 7. An artificial muscle, an angle detector, and a comparator constitute a loop by which the joint angle is controlled, while the loop formed by the artificial muscle, a power detector, a posture controller, and the comparator controls the center of gravity. In-

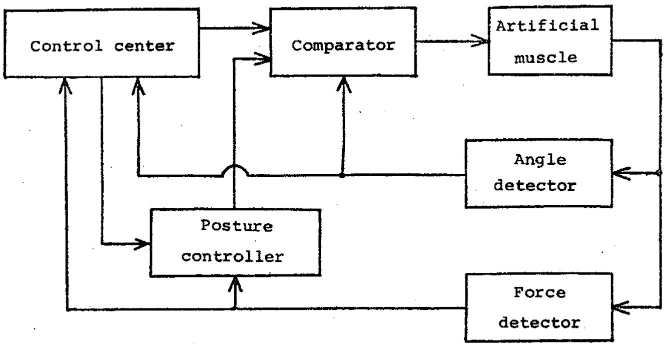


Fig. 7. Overall control system

formation from the angle detector and the force detector is fed to the control center to monitor the walking of the machine.

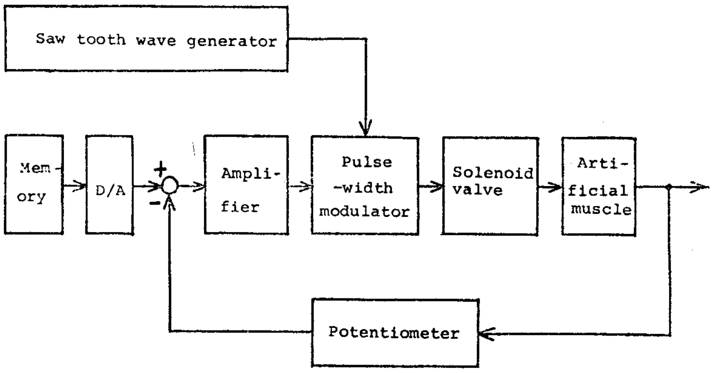


Fig. 8. Angle control

Description of the Control Units

Joint control system is shown in the block diagram of Figure 8. Angle command signals are sent from a memory, whose output signals have bit patterns of 0 and 1 and are converted again into analog angle commands by a digital-to-analog converter. The error between this analog signal and the signal detected by a potentiometer is amplified to operate a solenoid valve, which in turn controls the artificial muscle. Since the solenoid valve is operated by ON-OFF signals, the error signal which represents an analog quantity must be converted into ON-OFF signal. We employed a pulse-width modulation system instead of a two-value or three-value action system. The pulse width modulation system produces pulse outputs having a pulse width proportionate to the input signal so precise control can be obtained. The system's pulse frequency is 100 ms.

The control system for the center of gravity is shown in the block diagram of Figure 9. A semi-conductor strain gauge is attached and used as the pressure sensor to detect the reactions (Ff and Fb) of the foot at its front and rear ends. The difference between them, that is, Ff-Fb, is used in the control of the center of gravity.

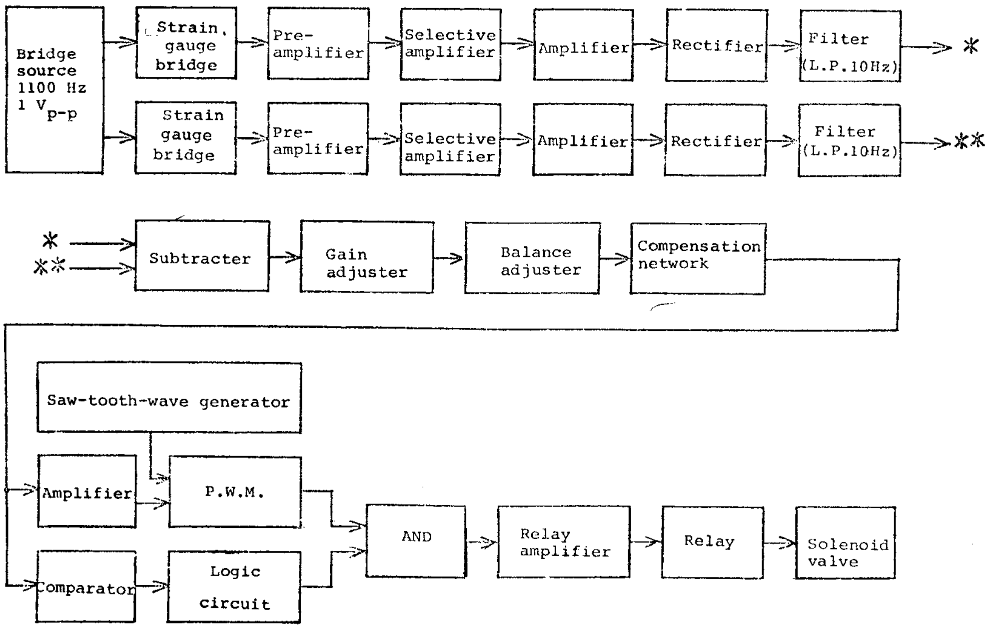


Fig. 9. Control of center of gravity

The difference (Ff-Fb) is amplified and is fed into a compensating network, the signal is processed by a nonlinear element, and the pulse-width modulation system is sent to the solenoid valve.

The compensating network Gc with the characteristics shown in Figure 10 was used.

$$Gc = \frac{S^2 + 2H\xi S + Wn^2}{S^2 + 2wnS + Wn^2}$$

ξ = small

H = 1.4

The use of this compensating network prevents oscillation in controlling the center of gravity; or, in case oscillation occurs, shortens its time.

When we give a command for directional change to the machine, it memorizes the command and acts accordingly when it comes to a point where it can change the direction of its walk. Depending on the condition of control, the machine can bend its joints at either of two speeds, high and low, which can be selected by the memory.

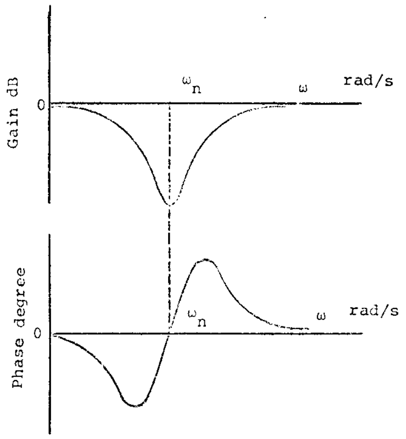


Fig. 10. Compensating network

Our walking machine incorporates a built-in mechanism for controlling the shifting of the center of gravity to the right or left. The timing of the shifting of the center of gravity to the right or left is controlled by the memory.

Overall Control System

The overall control system comprising the sub-control systems and memory mentioned in the preceding pages is illustraed in Figure 11. The right side of the memory is where the memory command is put into force. In the case of the ankle, three control modes - angle control, control of center of gravity, and free - are available. The memory is used in part to select only one of them and restrain the others.

The circuit on the left side of the memory controls the memory and produces a pulse when all the inputs - α, β, etc. - have been reduced enough in value; that is, when the memory command has been enacted, thus shifting the center by one. This causes a new memory output to come out. At this instant, the values of α and β are changed so that the control system functions to reduce them to 0. When stopping the walking machine, a stop signal should be given. When starting it again, give it a start signal. The memory capacity is 48 bits x 32 words. The 48 bits are used individually for angle control command, centroid control command of center of gravity, free, and shift command of

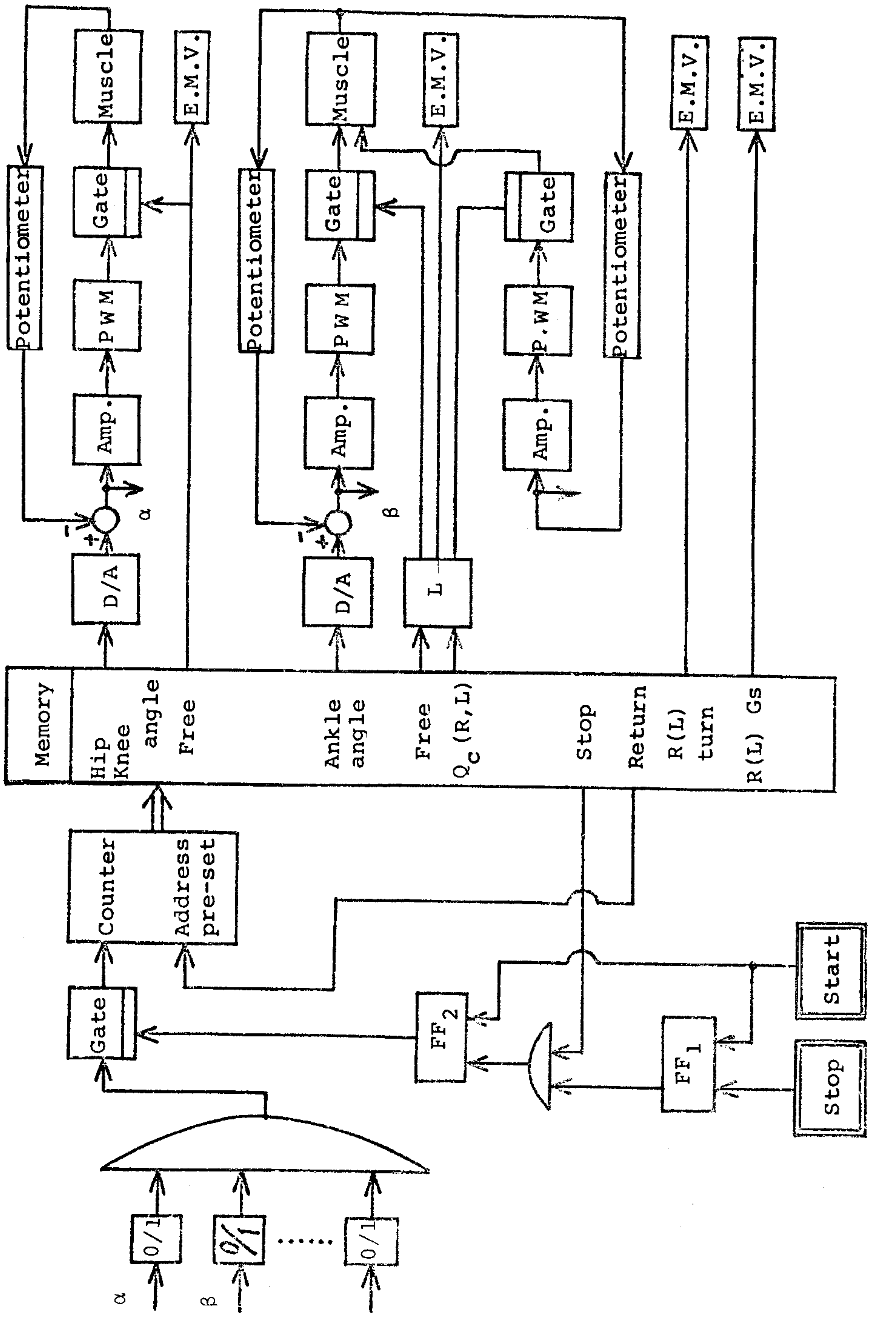


Fig. 11. Overall control system

center of gravity. The 48 bits constitute the necessary number of bits for a command for walking. But a walk does not necessarily require 32 words. In fact, 17 words were enough for walking on level ground, and 25 words were enough for walking on stairways.

Walking Experiment

Walk Programming

A walk program was prepared by taking out characteristic phases of walk in simulation of the slow pace of walk of a human being. Here is a brief description of walk on level ground.

1) The machine stands straight in its feet and is ready to start walking. The angles of all joints are controlled.
2) The machine stands on one of its feet (for example, on the right foot), with the other foot in the air. In this case, it shifts the center of gravity to the right ankle. The others are under angle control.
3) The left foot is thrown forward. The control method is the same as mentioned in (2).
4) The left foot touches the ground, so the machine now stands on both feet. Control of center of gravity on the the right ankle is realised. Depending on cases, the necessary joint is set free.
5) The center of gravity is shifted to the left.
6) That foot which is behind kicks the ground, or pushes the machine forward, to shift the center of gravity forward so the machine´s center of gravity now rests on the left foot.
7) Now the machine stands on the left foot alone. Control of center of gravity is now effected.
8) With the machine standing on the left foot, the right foot is thrown forward while control of center of gravity is kept on the left foot.

When the machine is in this state of (8), return to step (2) or (3) to advance the other foot. Keep controlling this process until the machine completes a cycle of walk. If a return command is written in next to the last word on y one-cycle program, it has been prepared.

Walk Action Experiment

Our walking machine walks relatively easily on level ground, but it is necessary to limit each step to 20 cm or less in order to maintain its stability in shifting the center of gravity to the right or left. One cycle of walk on level ground required about 1 minute and 30 seconds.

Our walking machine walked on a stairway but with less stability than in walking on level ground. Since it was not possible to narrow the steps of the machine´s walk in climbing stairways, the machine often swayed so much as to nearly fall when its center of gravity shifted from one side to the other. The steps of the stairway was 10 cm. Figure 12 shows how the walking machine walked up the stairway.

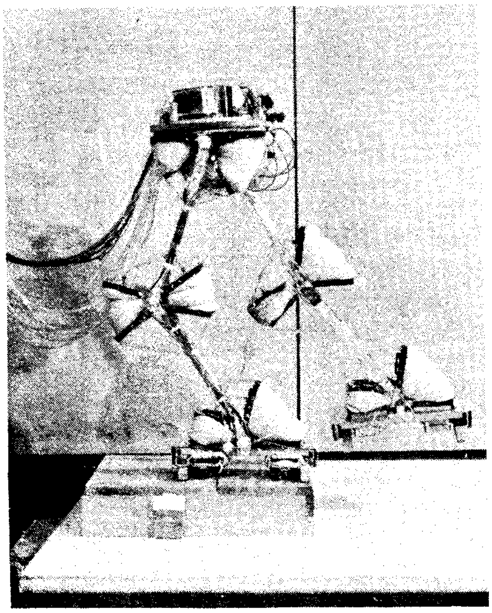


Fig. 12. WAP-3

The walking steps of the machine can be narrowed as desired in slope climbing. So there was no such problem as was encountered in the experiment of climbing a stairway. The slope had a 10% inclination.

Direction change is limited to level walking only because of the construction and control systems of the walking machine. When making the walking machine change its direction, do so as it stands on one foot; and when the machine shifts its direction with the other foot on the ground, it returns to straight walk. Direction changes were possible with the same degrees of stability as in the case of walking on level ground.

References

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/2/ Kato, I., Matsushita, S., Ishida, T., and Kume, K., "Development of Artificial Rubber Muscles", *Advances in External Control of Human Extremities*, pp. 565-582, 1970.