HYDRAULICALLY POWERED BIPED WALKING MACHINE WITH A HIGH CARRYING CAPACITY

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Summary

Locomotion is necessary for carrying various objects and recognizing the external world. For a new kind of locomotion a biped walking machine has been developed. This machine which is driven by hydraulic power, and which is programmed by semiconductor memories arrives automatically at a given goal point. Our objectives for a practical machine take into account as a minimum the following factors:

(1) the control of the center of gravity of the body in locomotion

(2) the turnaround

(3) carrying capacity (over 30 kg)

The prototypes of this machine (WASEDA LEG-5) are No. 3 and No. 4 that were manufactured respectively in 1969 and 1970 in our laboratory.

Introduction

This paper describes a mechanical experimental model that takes human biped gait into consideration. This model is a locomotion machine as a subsystem of the information-power-machine WABOT-1 to get external and internal information, form its own judgement on the situation, and automatically carry out a given job. Accordingly, it is necessary to provide the upper part of this machine with visual information processing equipment to recognize the external world and objects as well as the upper limbs for handling of objects, and to provide the capability of moving in any desired direction on level ground in maintaining stability.

Functions and Control System of the Walking Machine

Though a number of functions of a walking machine are required, they can be generaly classified into the following:

(1) To move in maintaining stability

(2) Adaptibility to environment

(3) Adaptibility to load

(4) Versatility in movement

As many of the walking machines are generally unstable in comparison with cars, the item (1) is the most important element in the design of a walking machine. For that reason the control system must maintain dynamic stability during movement and standstill as well. The adaptability to environment under item (2) is the ability to walk while coping with topographical changes such as level ground, stairs, and slopes, and to walk even in cases where there are small environmental changes such as unevenness, ditchs, etc. With respect to the item (3), the move itself of a walking machine is not the object which will be attained for the first time when it moves in carrying some load on the upper part of its body. It is for this reason that the ability to carry a load and adapt itself to load fluctuations is required. As regards the versatility referred to in item (4), the possibility of control of walking speed and direction as well as optional changing of walking stance and pace is desirable.

In this study, aimed especially at walking on level ground in a static stability range, a mechanical model satisfying at least the following three functions has been developed:

(1) Ability to move while maintaining stability

(2) Ability to change direction

(3) Ability to carry a certain load.

To move while maintaining stability requires control of the center of gravity of the body. Control of the center of gravity as referred to here means maintenance of center of gravity on the sole supporting surface during stance phase, and moving the center of gravity forward without being influenced by the position of foot on the swing phase or load fluctuation. For that purpose, the question of stability in the lateral direction and the question of correlation with stability in the walking direction have to be handled. We solved these questions by providing the sole with a degree of freedom in the lateral direction with respect to the former question and by contriving a proper gait pattern with respect to the latter.

Direction change is the most necessary function for arriving at a desired destination. This question was solved by providing the hip-joint with two degrees of freedom.

A program control, under which postures during walking are divided between swing and stance phases are set up and stored in semiconductor memories with a walking sequence being completed by selecting them sequentially, has been adopted.

History of Biped Walking Machine

As prototypes, WASEDA LEG-3 and -4 were made in 1969 and 1970, respectively /1, 2, 3/. The model before the W.L.-3 was the one having simulated one leg based on the anylysis of human gait. The W.L.-3 (Fig. 1) consists of two legs of a shell-type, provided with hip-, knee- and ankle-joints, with hip-joints of both legs being linked with a wood-frame pelvis. Each joint is provided with a double rod cylinder and the corresponding joints of the operator and the mechanical model with potentiometers as error detectors, thus constituting an electrohydraulic servo system. "Standing" as a premise to "walking" was realized for the first time by this model. As a result, a series of actions comprising sitting on a chair and so on were made possible.

The W.L.-4 (Fig. 2), with emphasis on a center of gravity control device, was intended to be a full-scale biped locomotion machine. As for the methods of gravity center shift, a method of providing rails on the upper part of the body and moving hydraulic parts left and right by means of the guide and a method of causing a rotary cylinder to swing a weight were employed. In addition, the tiptoe was proveded with a tiptoe-joint, the crotch region with the degree of freedom in direction change and the waist region with the degree of freedom in horizontal balancing of the upper part of the body. Concerning the mode of control, logical circuits were formed by digitizing various conditions of walking for setting up gait patterns and a sequential and combination system for non-synchronous sequential transition of them was adopted. The W.L.-4 was a model intended for automatization of biped gait, which, however, involved a number of problematical

Fig. 1. Operator and W.L.-3

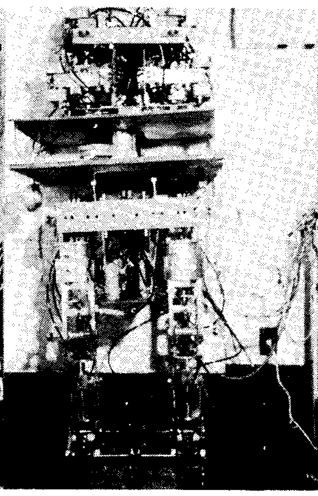

Fig. 2. W.L.-4

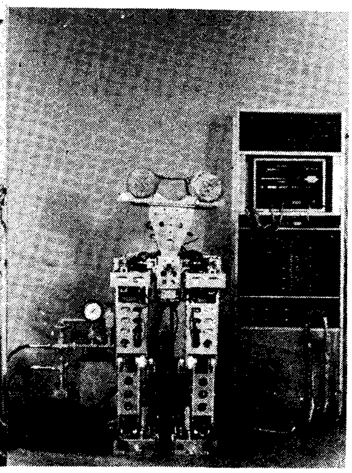

Fig.3. W.L.-5

Table 1 Specifications

Particulars	W.L.-3	W.L.-4	W.L.-5
Main body	Shell type with supports	Shell type with supports	Flat plate construction
Number of legs	2	2	2
Weight (kg)	13.4	Approx. 80	Approx. 130
Type of joint	Hinge joint	Hinge joint	Hinge joint
Joints provided	Crotch, knee, ankle, tiptoe	Waist, crotch, knee, ankle, tiptoe	Upper part of body waist, crotch, knee, ankle, sole
Gravity center shift	No	Movement of upper part of body	Tilting of whole leg
Power source	Hydraulic	Hydraulic	Hydraulic
Working pressure (kg/cm^2)	40	40	70
Final control element	Double rod type of hydraulic cylinder	Double rod type of hydraulic cylinder Rotary cylinder	Double rod type of hydraulic cylinder
Detecting means	Potentiometer	Potentiometer Limit switch Level	Potentiometer
Flow control valve	Meter-in circuit	Meter-in & meter-out circuits	Meter-in & meter-out circuits
Flow control system	Digital (2-line diversion)	Digital (2-line diversion)	Digital (Pulse control)
Control system and operation pattern	Feedback	Feedback Sequence Fixed pattern	Sequence Variable pattern
Performance	Follow up lower lower extremity of living body	Gait with double leg support	Straight walking Direction change Load-carrying

points and could not attain locomotion. Greately improved on the basis of the W.L.-4 is the W.L.-5, which does provide locomotion (Fig. 3).

Biped Walking Machine

Construction of the mechanical model

Each joint is of the hinged type with one degree of freedom. The number of joints of the mechanical model is 11 in all as shown in Figure 4, roll joints (two), ankle joints (two), knee joints (two), hip joints (two), waist rotation joints (two), and a lateral joint (one) in the upper part of the body. The roll joints and the lateral joint in the upper part of the body are located in the roll axis of the mechanical model and effect shift of the center of gravity in the lateral direction. First, the upper part of the body is tilted left or right by the lateral joint to aid gravity center shift in the lateral direction. Further, the roll joints are of a double construction at the sole as shown in Figure 5 and at the time of single-leg support the outer frame remains on the ground while the inner frame linked with the leg proper inclines, causing the center of gravity to fall on the support plane.

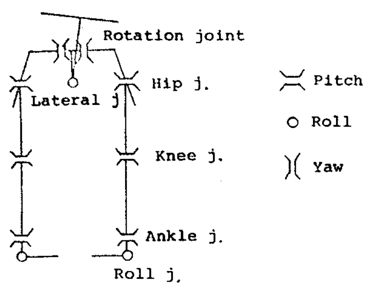

Fig. 4. Degrees of freedom of mechanical model

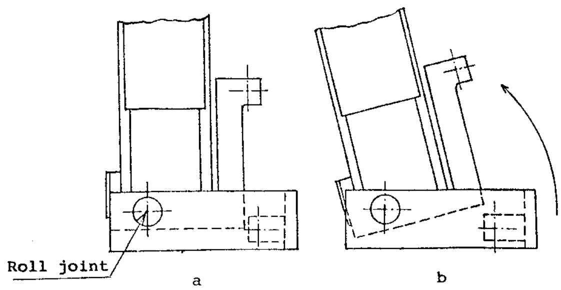

Fig. 5. A front view of right foot

The center of gravity shift in the walking direction is effected by synergistic movements of ankle, knee, and hip joints in the direction of the pitch axis. The waist region is divided in 3 blocks, or right leg, center region to support the upper part of the body, and left leg (Fig. 6). Change of direction is made by rotating the waist by means of the joints about the yaw axis in the rear middle part. The lateral joint in the upper part of the body is fixed to the center region.

In order to ensure strength sufficient for supporting the entire weight and for fastening of the cylinder fitting position as well as to attain high accuracy with a simple construction, a box type of construction comprising combined flat plates was employed in the fabrication of the shell. Hydraulic power is employed and all the hydraulic circuit components except the hydraulic power unit are incorporated in the mechanical model proper. High strength aluminium alloy is used principally throughout the mechanical model, and ball bearings are provided at the joints. The weight is approximately 130 kg and a load of 30 kg is possible.

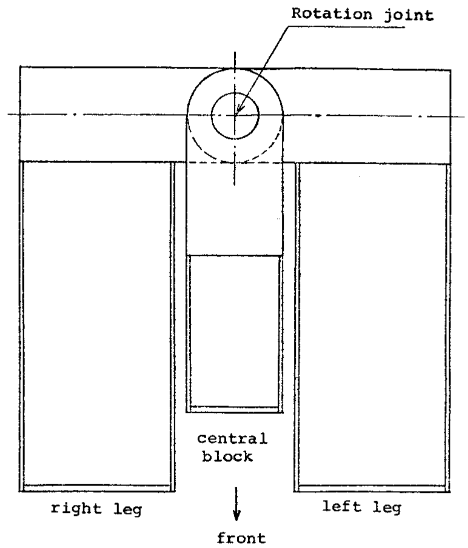

Fig. 6. Mechanism of rotation joint.

Construction of the Hydraulic System

The hydraulic system consists of a double rod cylinder as the actuator, a three-position solenoid valve of a closed center type to control direction and flow of pressurized oil, a two-position solenoid valve making possible the free condition of the cybernetic actuator /4/, and a power unit (Fig. 7). Three types of basic circuits for flow control are used: meter-in, meter-out, and bleed-off circuits. Generally, the meter-in circuit displays excellent performance in respect to cylinder overhoot and setting time is employed, whereas the meter-out circuit is effective for preventing overrun against load in the negative direction when piston is liable to be pulled. Therefore, except when the meter-in circuit is provided for direction change, the meter-out circuit is employed in the system. The working pressure is 70 kg/cm^2.

Control Circuit

A program control system is employed. That is, consecutive walking patterns are divided into some characteristic phases to provide limitations for the working conditions of the actuator.

Therefore the continuous action of walking is replaced by sequential motion based on the phases. Such a gait program is stored as digital data in the memory block. Accordingly, the walking

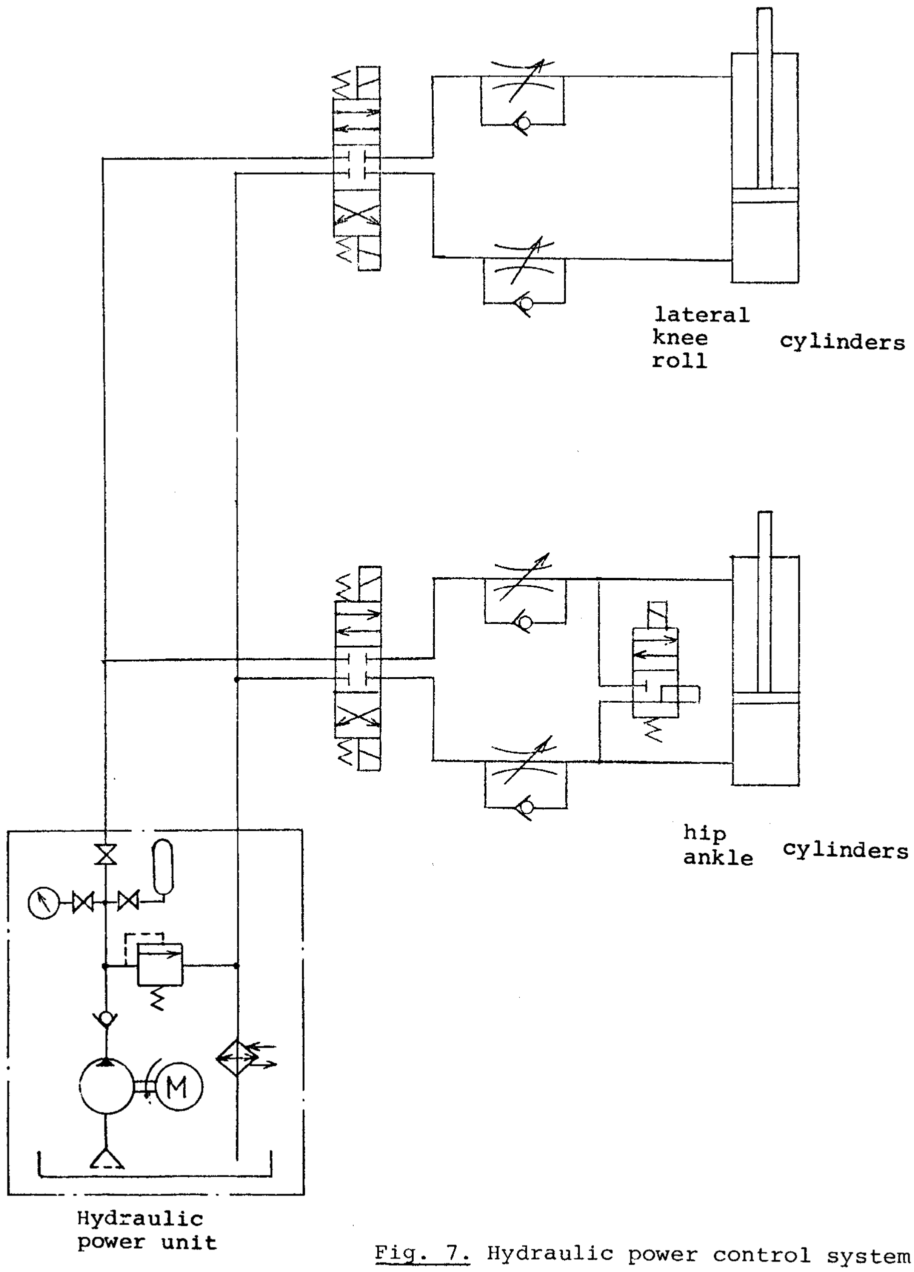

Fig. 7. Hydraulic power control system

pattern can be modified by rewriting data in the memory block. Further, for changing the gait, a system of an advancing program address by means of count pulses transmitted at a certain interval, that is, a synchronous control system is employed. Speed control of the mechanical model, or flow control of the hydraulic circuit, is carried out by applying certain types of pulse train to the input of the three-position solenoid valve.

The block diagram of the control system (Fig. 8) can be divided into the input circuit, memory block, output circuit, and mechanical model. The input circuit generates count pulses by the walking command to drive the scale counter and advance the program address written in beforehand. Data of the designated address is applied as a desired value to the output circuit. To make the mechanical model follow the desird value, each joint is provided with a rotary type of potentiometer, and, with its movement as feedback signal, an electrohydraulic servo system performs between output circuit and mechanical model. Because an on-off control solenoid valve is employed, a circuit to discriminate between positive and negative of the analog differential voltage between desired and detected values and convert it into on-off signal is required. Pulse signal to be used for flow control is combined with this on-off signal.

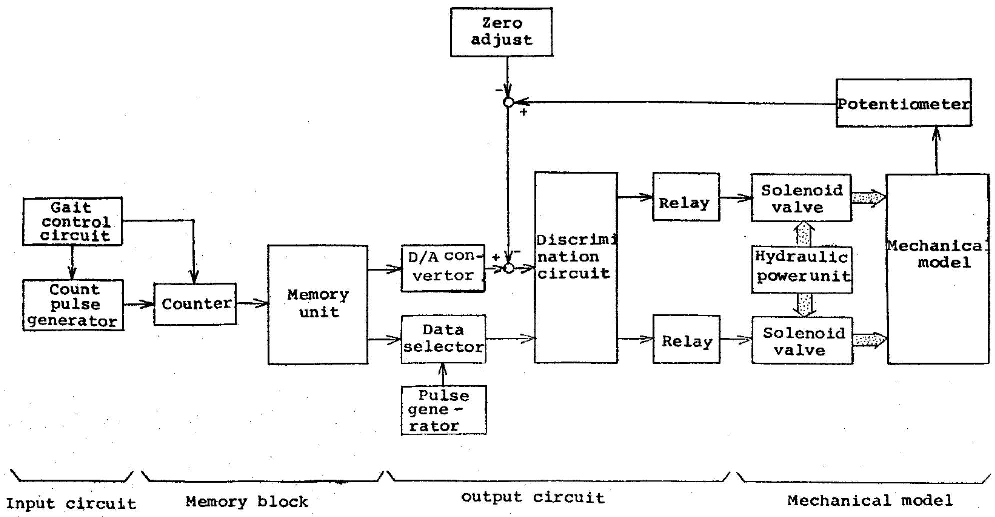

Fig. 8. Block diagram of the control system.

Experiments on Performance

At present, stright walking (with a walking stance of approx. 20 cm) and direction change on level ground are carried out by manual operation of a switch. The walking pattern is shown in Figures 9 and 10. The walking pattern is considerably modified in comprison with man´s normal walking pattern. When a man walks at

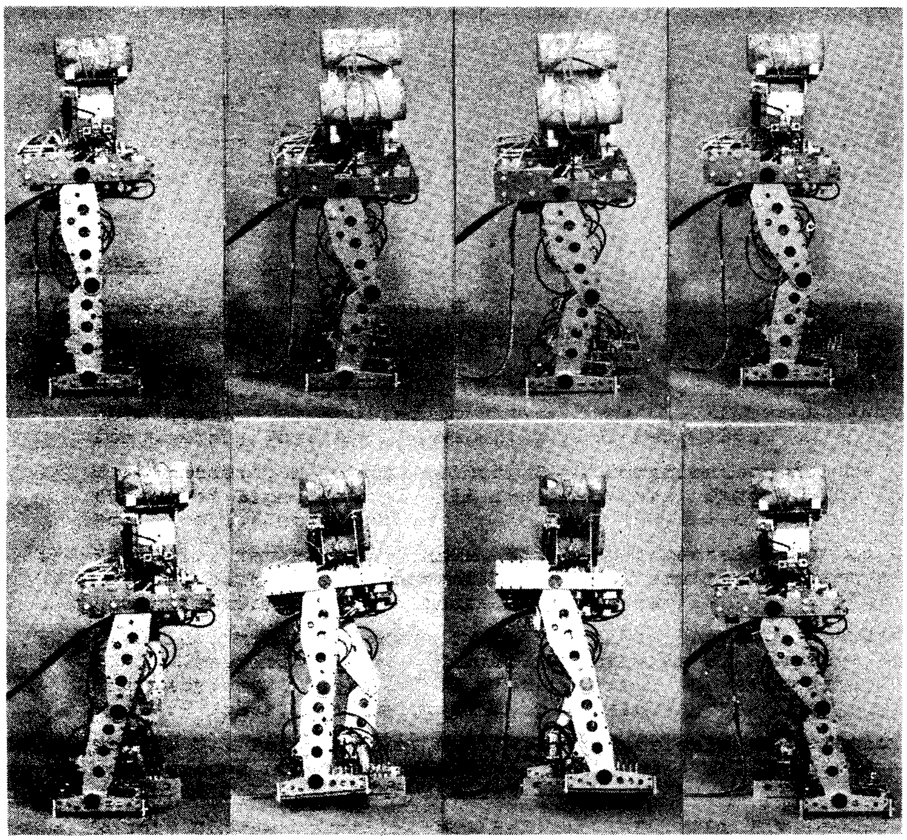

Fig. 9. Walking pattern.

normal speed, he effects gravity center shift in utilizing inertia, not always maintaining a static stability. However, when the walking speed is quite low, for instance when walking in darkness, static stability is always maintained. For walking of the mechanical model, a pattern in which static stability is maintained has been employed.

In producing a biped gait, a single-leg support should be possible. For that purpose, gravity center shift in the lateral direction is required. When no load is imposed on the upper part of the body, a trigger action is required at the roll joint of the swing leg, but when a load is carried, gravity center shift takes place easily through the lateral joint of the upper part of the body, leading to a single-leg support. The center of gravity shift in the walking direction is carried out during a biped support, which places the ankle joint of the swing leg and the hip joint of the stance leg into a free condition to drive the remaining joints (hip, knee, and ankle) for a forward shift of the center of gravity. It takes about two minutes to walk a cycle in the case of manual operation.

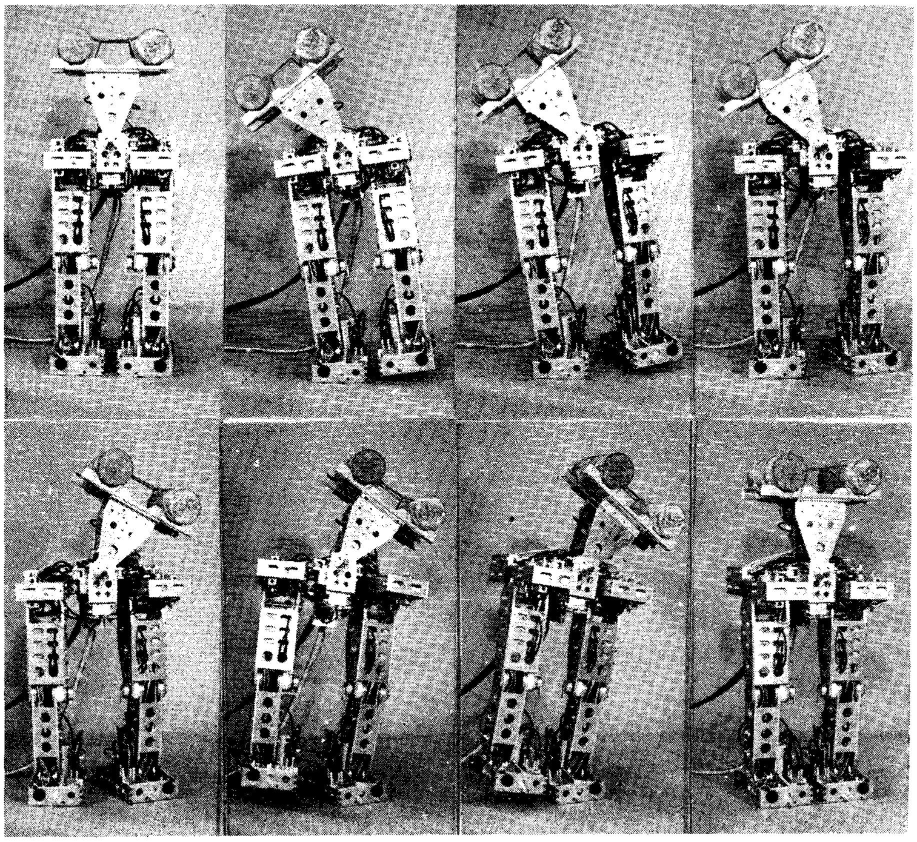

Fig. 10. Turning pattern.

The change of direction is made from a single-leg support by causing rotation of each block sequentially. In this way, the change of direction of approximately 30 deg. can be made in one cycle.

Outlook for the Future

As described above, straight walking and the change of the direction on level ground by manual operating have been realized, but to make the W.L.-5 a biped walking machine having the functions of versatility in movement and adaptability to load and environments, the following control mechanisms are deemed necessary:

(1) Mechanisms to select and decide an optimum gait and its speed according to environmental conditions
(2) Mechanisms to generate gait sequence
(3) Mechanisms to actually move the legs properly according to the gait sequence
(4) Control mechanisms for stabilization of gait.

These mechanisms can be expressed as hierarchy structures as in Figure 11. At present, control circuits to make possible items (2) and (3), are in the course of adjustment. The model will be completed as a WABOT by coupling it with a computer, a visual system, and a tactile system. A feedback loop for gait stability and a feedback loop for speed and gait determination will be completed. The feedback loop for gait stability is intended for stabilization of gait on the basis of information on the posture and sole condition of the walking machine, and should gait stability be not able to be maintained, the actuator will act so as to maintain stability by an automatic correction of a part of the gait. Conversely in the feedback loop for speed and gait determination, the computer will judge information from the visual and aural systems to give various walking commands. Under the above concepts, the author is pushing forward the study to bring the W.L.-5 to completion.

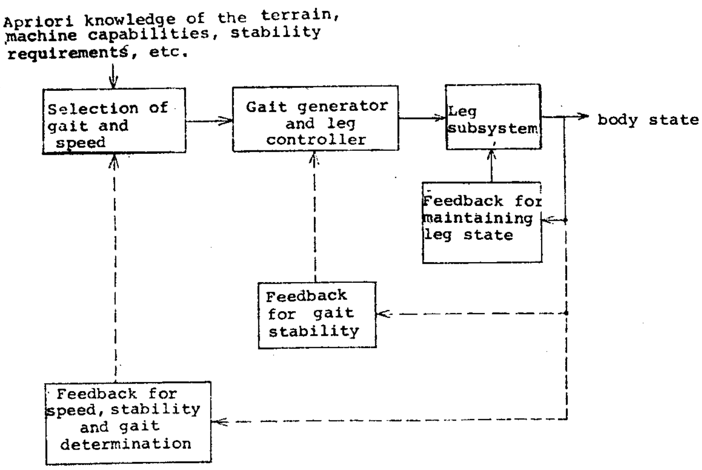

Fig. 11. The organization of a general legged locomotion machine.

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