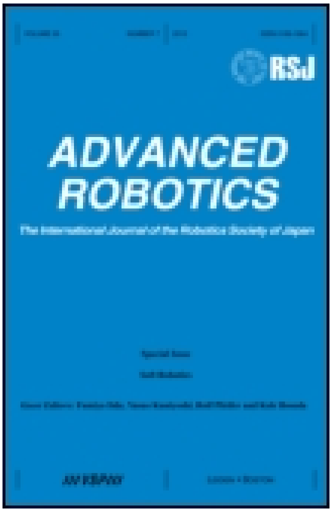

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The gait control system of a quadruped walking vehicle

Shigeo Hirose [a], Yasushi Fukuda [b] & Hidekazu Kikuchi [c]
[a] Faculty of Engineering, Tokyo Institute of Technology, 2-12-1, Ōokayama, Meguro-ku, Tokyo 152, Japan
[b] Toshiba Ltd.
[c] Asahi Chemical Ind. Co., Ltd.
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Paper

The gait control system of a quadruped walking vehicle

SHIGEO HIROSE,* YASUSHI FUKUDA† and HIDEKAZU KIKUCHI‡
**Faculty of Engineering, Tokyo Institute of Technology, 2-12-1, Ōokayama, Meguro-ku, Tokyo 152, Japan*
†Toshiba Ltd.
‡Asahi Chemical Ind. Co., Ltd.

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Abstract—A walking vehicle has potential capability to be developed to an off-road machine with high mobility and adaptivity by using the coordination control of its multi-degrees of freedom. There have been several discussions on the gait control of a walking vehicle, although few have mentioned the total gait control system and any sub-systems integrated into the total structure. This paper discusses the gait control system based on a quadruped walking vehicle developed by the authors. At first, the premises for the discussion are confirmed. Then, the total structure of the control system, consisting of three levels named A, B and C, is clarified. The control algorithm of each level is studied in detail, particularly the three sub-systems belonging to level B, i.e. gait control in xy coordinates, the same in z coordinate and trajectory control of legs taking account up/down swinging. The control algorithm at level C, which regulates the basic reflex motions, is specifically discussed. Finally, these discussions are verified by walking experiments of a model TITAN III. The joystick control of omni-directional motions and adaptive locomotion over irregular surfaces are successfully demonstrated.

1. INTRODUCTION

Legged animals such as the horse, leopard or lion, run around skillfully adapting themselves to their environment. They walk efficiently and rhythmically on a plane, look carefully for footholds in rocky tracts, jump over brooks and gallop freely on deserts.

The walking motion of those animals are found to be controlled by the hierarchy nervous control system, including the innate walking rhythm created at the motor nerves in the brain and vertebra, and rhythm adjustment by the hemicerebrum and brain stem responding to centripetal stimulation from the feet [1]. Unfortunately, however, little investigation has so far been made into the concrete mechanism of those nerve systems, including the learning process.

On the other hand, a variety of studies have been conducted on artificial walking machines and research on gait control was reported [2–6]. The authors have made several basic studies in this field [7–15]. Those observations, however, were mostly limited to the subjects related to the sub-systems constituting a part of the gait control system. No information is available at present concerning comprehensive studies of the total gait control system so far as a four-legged walking machine is concerned.

On this account, this paper makes a presentation on an overall mechanism of the control system of a quadruped walking vehicle and the sub-system of the major internal structure from both a general and comprehensive viewpoint, and consequently proposes a concrete concept for the future development of walking robots.

Metaphorically speaking, the current study is ultimately aimed at producing 'an artificial horse', and aims to contemplate how to construct an intelligent system which is a counterpart of the horse brain. A man mounted on a horse does not need to instruct the horse how to move the four legs. The horse itself senses terrain ahead and keeps on walking with safe and efficient motions. If such a large stratous intelligent structure comprising rider and horse could be transformed into a man–robot system, a walking machine becomes a rough-terrain-moving-platform which can be easily controlled in a manner similar to an automobile.

The control system may be called an 'intelligent suspension' of an artificial mobile machine. An automobile absorbs or compensates for some irregularities of the land surface by means of a passive suspension system. On the other hand, the control system of the walking vehicle intended by the current study adapts to small irregularities by sensing the terrain with its visual and tactual sensors, and makes autonomous evading motions when facing obstacles which are sensed to be impossible for step-over. This means that the machine can positively and intelligently cope with rough terrain. In other words, it can be described as one of the well advanced modes of suspension devices.

In order to systematically discuss the basic structure of a walking vehicle control system, the present paper first defines several fundamental issues (in Section 2), clarifies the overall picture of the hierarchy intelligence structure (in Section 3) and introduces the basic concepts in the walk control (in Section 4). As for each sub-system, a generally-practiced predictive gait-determining system is discussed in details (in Sections 5, 6, 7 and 8), and subsequently emergent motions are explained (in Section 9). Finally, the accuracy of those discussions is confirmed by a walk-control demonstration using the experimental machine TITAN III actually implemented with the control system design based on the studies (in Section 10).

2. DEFINITION OF PROBLEMS

2.1. *Main codes*

C_i: Center of the reachable area (rectangle) on the xy plane of a leg i.

D_u: Landing-point-searching area of swung leg u.

$D(P_a, P_b)$: Length of a vector from point P_b to P_a projected on the xy plane.

$D_x(P_a, P_b)$: The x-directional constituent of a vector from point P_b to point P_a.

$D_a(P_a, P_b)$: $= D_x(P_a, P_b)\cos\alpha + D_y(P_a, P_b)\sin\alpha$.

E_k: Coordinate system in which the xyz coordinates are combined to the torso direction, as shown in Fig. 1, with the center of gravity of the machine being set at the origin, at the step-switching point N_k.

$f, \bar{f}, r, \bar{r}$: Against any designated leg, a fore-leg on the same side (either left or right side) is f, a rear-leg is r while, a fore-leg on the opposite side is $\bar{f}$ and rear-leg is $\bar{r}$.

$g_i, g_{ix}, g_{iy}, g_{iz}$: Movable distance of the center of gravity along the track L_G, being restricted by the reachable area when leg i is touching the ground, and the constituents thereof in the xyz coordinates.

g_{0max}: Maximum movable distance of the center of gravity along track L_G in the supporting phase at the step S.

g_{max}: Maximum movable distance of the center of gravity along track L_G at the step S.

g_0: g_{0max} taking account of the standard stability margin s_0.

g: g_{max} taking account of the standard stability margin s_0.

g_u: $g-g_0$.

g_z: Distance in which the center of gravity moves to the z direction at the step S.

H: Average height of the center of gravity from the ground surface.

h_{up}: Lifting range of a swung leg in the go-up phase.

h_{dwn}: Descending range of a swung leg in the go-down phase.

i: Sign for a leg ($i=1$–4).

j: Sign for a swung leg.

J_u: A point at which swung leg u is supposed to exist at the step-switching point N_{k+1} (on the coordinate E_k).

k: Number of step or step-switching point.

$L(P_a, P_b)$: Straight line connecting point P_a with P_b on the xy plane.

L_G: Projected line of trajectory of the center of gravity on the xy plane.

n: Sampling frequency at timer interruption control.

N_k: The k-th step-switching point.

P_a: Point indicated by code a.

P_u: Position of swung leg u at N_k (on the coordinate E_k).

s: Longitudinal stability margin [2].

s_0: Standard stability margin. Minimum value of stability margin s in one cycle of standard gait.

S_k: The k-th step (on the assumption that the machine is in the S_k state, in the analysis).

$t_{spt}, t_{up}, t_{rtn}, t_{dwn}$: Time of support phase, go-up phase, return phase and go-down phase of swung leg in a step.

T_k: The k-th step time ($=t_{spt}+t_{up}+t_{rtn}+t_{dwn}$).

T: Cycle time of standard crab-walk gait.

u: Sign for a swung leg.

u^*: A leg which was in swing before a swung leg u in the standard gait.

v_x, v_y, v_z: Swing velocities of a leg in the x, y and z directions, respectively.

V_x, V_y, V_z: Maximum mechanical swing velocities of a leg in the x, y and z directions, respectively.

$v_G, v_{Gx}, v_{Gy}, v_{Gz}$: Shifting velocity of the center of gravity and the constituents thereof in the x, y and z directions, respectively.

$V_G, V_{Gx}, V_{Gy}, V_{Gz}$: Maximum shifting velocity of the center of gravity and the constituents thereof in the x, y and z directions, respectively.

$x^*, y^*, z^*, x_0, y_0, z_0$: Parameter defining the reachable range of a leg as shown in Fig. 1 (positive value).

$\left.\begin{matrix}\delta x_{out}, \delta x_{in}\\ \delta y_{out}, \delta y_{in}\\ \delta z_{out}, \delta z_{in}\end{matrix}\right\}$: Deviation latitude between the mechanical reachable range and the same on the software used in the analysis (See Fig. 1).

x_{rtn}: Swing range of a swung leg against the center of gravity in the return phase.

$x_i^m(t), y_i^m(t), z_i^m(t)$: The xyz coordinate potentiometer monitor readings of leg i at time t.

$x_i^d(t), y_i^d(t), z_i^d(t)$: Reference signals to the xyz coordinate servo system of leg i at time t.

α: Crab-walk angle.

α_c: Switching critical angle of xy directional crab-walking gait.

β: Duty factor.

θ_p, θ_r: Pitching and rolling angles obtained from the posture sensor.

ϕ_G: Pitching angle of trajectory of the center of gravity at step S_{k+1}.

2.2. Walking machine to be discussed

It is assumed that a walking vehicle should have four legs as shown in Fig. 1, based on the authors' studies in the past, with each leg having a rectangular reachable area [14, 15]. The walking machine is assumed to have the coordinates system, with the center of gravity (hereinafter, 'center of gravity' denotes 'G' which is the center of gravity of the torso) being the origin, the x-axis in the front/back direction of the torso, y-axis in the left/right direction and z-axis in the top/bottom direction. The coordinate system for the analysis is based on the body coordinates E_k at the step-switching point N_k (see Section 4.1). The legs are named Legs 1–4, to match the quadrant of the xy coordinates as seen in Fig. 1. The reachable area of a leg from the control viewpoint is indicated by x^*, x_0, y^*, y_0, z^* and z_0 as in Fig. 1. Where, the mechanical reachable area of the walking machine, as shown by broken lines in Fig. 1, is designed to be wider than that of the software to allow some area in reserve (δx_{in}, δx_{out}, δy_{in}, δy_{out}, δz_{hgh} and δz_{low}) in the xyz directions. The use of the margins will be discussed in Chapter 6.

The walking machine is assumed to be equipped with a visual sensor which can see relatively nearby terrain ahead during locomotion so that the gait control is assumed to make use of such information. Also, while walking, the robot is assumed to control its posture so as to keep the torso horizontally. In the future, an inclined posture of the torso should be considered in order to cope with up/down motions on steep slopes. At present, however, this horizontal posture is desirable for the stability of mounted equipment to walk over surfaces with ordinary irregularities. This type of control is necessary for exerting the effect of a Gravitational Decoupled Actuation (GDA) proposed in the past [15].

2.3. Moving environment

The environment in which a walking machine is expected to locomote is 'rough terrain' unsuitable for a conventional automobile. But, the actual status of 'rough terrain' is too diverse to describe in a simple manner. So far, several studies have been reported on the classification and quantitative description of 'rough terrain'. This paper adopts five types of classification [8], as shown in Fig. 2.

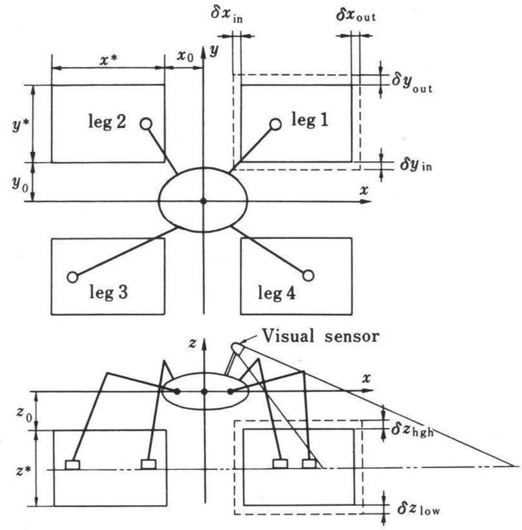

Figure 1. The dimensions of reachable area. The reachable areas for control (solid line) are set smaller than mechanical limitation (dotted line).

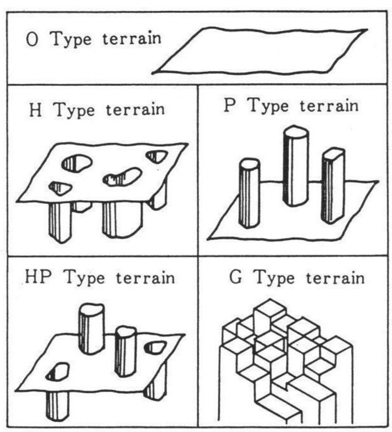

Figure 2. Classification of terrain.

The O type terrain means a surface on which standard rhythmical walk is possible. A flat plane belongs to this O type, although it does not need to be a complete level surface. Ground with some irregularities can be classified in this type if the irregularity-absorbing gait of Section 7.1 is considered.

The H type terrain is a surface with deep holes in which the legs of the walking machine do not reach the bottoms. On the H type terrain, the walking vehicle cannot choose those holes as leg-landing positions but can pass over such holes.

The P type terrain denotes a surface having poles or rocks taller than the dimension of the walking vehicles. On a P type terrain, a robot should avoid putting its legs on the poles and rocks and should try to cross over them.

The HP type means a mixture of the H and P types, while the G terrain is the discrete expression of the surface height in the form of a matrix.

Usual rough terrain is supposed to be of the G type. So, when a robot is walking on rough terrain, the map of the forward terrain is fed to the walking vehicle from the visual sensor. At first, it constitutes the G type terrain based on the input range signals and then is reformed to the HP type, taking account of the dimensions and moving mode of the robot. The HP type is stated in the coordinate system E_k (Section 4.1). This paper will develop a discussion mostly based on locomotion on the H type terrain.

2.4. Conditions for stability

One of the major reasons of designing a quadruped walking vehicle is that such a structure can reasonably realize both static and dynamic walks. The four-leg system, making use of its 12 degrees of motion freedom, enables the vehicle to walk pliably. It can change speed from slow-but-stable motion in static posture to dynamic fast locomotion, adapting itself to the states of terrain. Of the static and dynamic walks static locomotion is more basic and less complicated than the dynamic walk in terms of the control algorithm and analysis of motions. The authors believe the concept of the 'stability margin' of the static locomotion can be expanded to dynamic walks for further analysis. On this account, the current study at first focuses on the maintenance of 'static stability' to discuss the walk control.

The concept of 'stability margin' [2] is known as the yardstick for measuring the static stability. The value is given in the relation between the center of gravity and the polygon of supporting legs, and is also governed by the height of the center of gravity and compliance of the legs [7]. For simplicity of analysis, however, this paper employs the longitudinal stability margin [2], s, as the primary approximate value. It is the minimum distance from the center of gravity to a side of the polygon of the supporting legs on the gravity-center-advancing orbit L_G. The minimum value of the longitudinal stability margin s in the standard crab gait is specially named 'standard stability margin s_0', to be used as the yardstick to bring forth a 'convergence-to-standard type free gait' (Section 4.2).

3. CONSTRUCTION OF CONTROL SYSTEM

A walking machine control system is known to be preferable when classified into three hierarchies as shown in Fig. 3. Level A corresponds to a human operator. Judgement at Level A is made from overall viewpoints of both terrain and operational purpose, independent of the mechanical restrictions of the walking machine. Level A creates the mobile strategy for a robot in general. The studies of Level A are tentatively put aside since this paper intends to discuss the structure of an intelligent control system which is the brain of an 'artificial horse', as previously explained.

Level B is an intelligent gait control system and is further divided to four sub-levels. Level B_1 checks the route and speed commanded by Level A against the map of the terrain laying just ahead and makes a local route rectification to ensure efficient walking and obstacle avoidance. The route means a three-dimensional orbit of the center of gravity when the robot evades or strides over a hole on the H-type terrain, or follows the pliantly irregular surface on the O-type terrain. The key issues

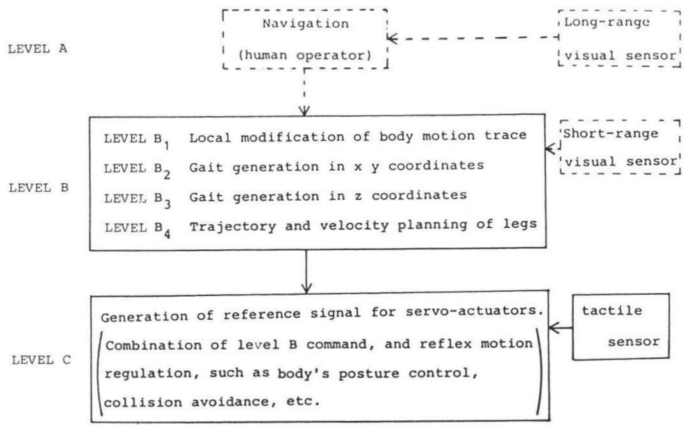

Figure 3. Hierarchy control system of the walking vehicle.

at this level are the communication with the visual sensor for terrain information and the artificial-intelligence-approach for route-finding. However, the details will not be stated in this paper as the authors' observations of Level B_1 need to be closely scrutinized before reaching any conclusion [11].

Level B_2 gives three kinds of control values in *xy* coordinates, i.e. the sequence of leg swing, the moving distance of the center of gravity and the landing points of the legs. Only the sequence of the leg swing and the geometrical positions of the legs are determined at this level. It does not predetermine anything about velocity.

Level B_3 determines the gait of the center of gravity (i.e. the height of the supporting legs in the *z*-coordinate direction).

Level B_4 generates specific reference values in terms of the moving velocity of the center of gravity and the returning trajectories and velocities of the swung legs to be input to the servo system for walks based on the sequence determined at Levels B_2 and B_3.

Level C, the lowermost level, executes control equivalent to the reflex action adjustment carried out in animals at their brain and vertebra. It inputs continuously the positions of the legs and the state of the sensor in order to generate motions coping with emergent situations, while implementing the commands given from the upper levels.

This paper discusses Levels B_2, B_3 and B_4 and Level C as shown in Fig. 3, which make the nucleus of the mechanical controls of a walking vehicle. The short range visual sensor has not yet been mounted on any experimental machine for actual walking tests, although its existence has been assumed in theory and computer simulation. Therefore, it is surrounded by broken lines in Fig. 3.

4. INTRODUCTION OF THE BASIC CONCEPTS IN WALK CONTROL

The basic concepts which are important in the investigation of walk controls are clarified in the following sections.

4.1. Step S_k *and step-switching-point* N_k

Provided that swung legs do not move up/down, and repeat advancing/returning motions only, the interval from the completion of return of a swung leg till the completion of the return of the next swung leg is named 'Step S_k', where k stands for the number of steps after initiating the walk. When swung legs, as shown in Fig. 8, are repeating three-dimensional motions consisting of four phases, i.e. support, up, return and down phases, 'Step' means the interval from the completion of the 'down phase' of a swung leg to the completion of the same of the next swung leg. A step-switching-point N_k is the moment when Step S_k completes the down phase. In general, however, the moment when a down phase is complete does not necessarily agree with the moment when a swung leg touches the surface but with some moment when the swung leg shifts to an advancing phase. The significance of defining the step for discussing the gaits is explained in the Section 4.5, in which an irregularity-absorbing gait is presented.

The control system discussed in this paper foresees the positions of the center of gravity and the leg-landing positions of a walking machine when it reaches the step-switching points so as to generate smooth motion in the lower level systems.

4.2. Convergence-to-standard type free gait

Determination of gaits seems to have two approaches from the viewpoint of which gait mode is to be selected:

(1) Standard Gait: The best rhythmical gait in terms of walking efficiency and stability on a flat surface.

(2) Free Gait [4, 5]: The non-constant gait adjusted for rough terrain. The gait selects routes, searching for safe footholds, avoiding obstacles and maintaining static stability.

If the capability of a robot is limited to the standard gait it cannot walk stably on rough terrain. On the other hand, free gait on an irregular surface is not the most efficient and stable gait when the robot comes back to a flat surface. On this account, the present control system is designed to make an adaptive walk, continuously checking routes and velocity against sensed terrain laying ahead and trying to converge to the standard gait as long as the terrain permits. This mode is named 'convergence-to-standard type free gait'.

4.3. Standard crab-walk gait

The concept of a standard gait should be clarified in order to realize the convergence-to-standard type free gait. As previously pointed out [2, 16], it is the wave gait that forms the standard gait in the straight forward advance by a machine having more than four legs. The wave gait of a four-legged robot is specifically called crawl gait. 'Crab walk' is defined as straight walk with the direction of walk, apart from the direction of the torso; it is understood that no investigation has been made in the past about the standard gait of the crab walk. For a walking machine with multiple degrees of freedom, omni-directional mobility is one of the most important functions. In fact, such a robot is expected to frequently move toward many directions. It is, therefore, essential for the elucidation of the standard gait in crab walk.

In this respect, the present study develops the standard crab-walk gait at this stage. The gait is obtained only for geometrical relations of legs on the xy plane. As a walking machine is symmetric in fore–aft and right–left directions, the study tentatively concentrates on the range of $0 \leqslant \alpha \leqslant \pi/2$ (where, α is an angle made by the crab-walking direction with the positive direction of x-axis, and is named the 'crab-walk angle'). The trajectories of the four legs are set to be point-symmetric with respect to the center of gravity, based on the condition to maximize the static stability. In order to restrict the leg trajectories within the scope that will not invalidate the generality, this study includes a condition that the trajectory of leg i passes the midpoint C_i of the reachable area R_i, regardless of the crab-walk angle α.

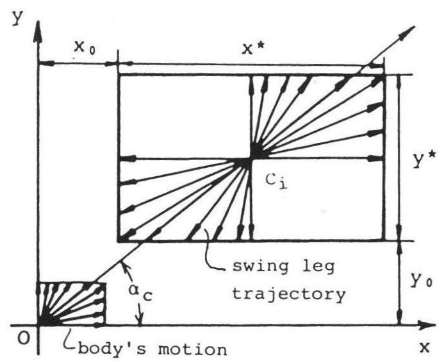

Figure 4. The standard stroke motion of a leg and the coordinated motion of the body at various crab angles.

Fig. 4 shows the stroke trajectory of a foot-tip in the reachable area. The stroke length λ^* is:

$$\lambda^* = \begin{cases} \dfrac{x^*}{\cos\alpha} & 0 \leq \alpha \leq \tan^{-1}\left(\dfrac{y^*}{x^*}\right) \\[2ex] \dfrac{y^*}{\sin\alpha} & \tan^{-1}\left(\dfrac{y^*}{x^*}\right) \leqslant \alpha \leqslant \dfrac{\pi}{2}. \end{cases} \tag{1}$$

Motion sequence of the swung-legs is shown in Fig. 5. It shows a case for $\alpha = 16°$ (0.28 rad). This figure shows xy direction gait only and does not include both z-direction and irregularity-absorbing gait, which will be explained later. It contains all of the basic information necessary to understand the timing of the standard gait.

The example shown in Fig. 5 is basically the same as the crawl gait when the machine walks straight ahead in the x-direction as shown in Fig. 6(a). However, in Fig. 6(b), in which $\alpha = 74°$ (1.3 rad), the leg-swing pattern is Legs 1–3–2–4, and is different from 1–3–4–2 of the x-directional crawl gait of Fig. 6(a). This fact suggests the existence of a critical angle α_c at which the x-directional crab-walk gait switches to the y-directional crab-walk (0–$\pi/2$). Obviously, the critical angle α_c is the crab-walking angle passing the point C_i. This leads to:

$$\alpha_c = \tan^{-1}\left(\frac{y_0 + (y^*/2)}{x_0 + (x^*/2)}\right), \tag{2}$$

in short, it takes an x-directional crab-walk gait when $0 \leqslant \alpha \leqslant \alpha_c$ and y-directional crab-walk gait when $\alpha_c \leqslant \alpha \leqslant \pi/2$. When $\alpha = \alpha_c$ it can take both gaits, which is, however, undesirable because of the zero stability margin as the center of gravity

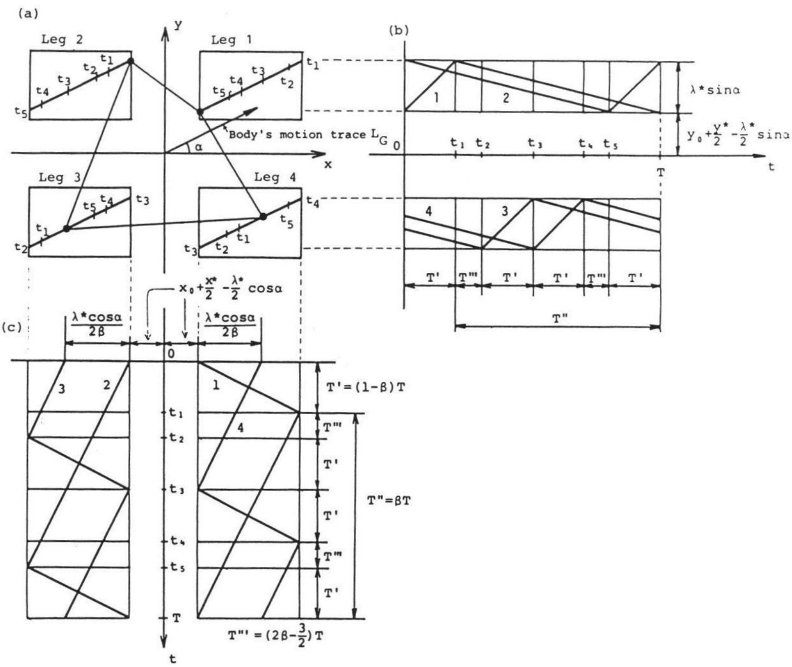

Figure 5. Relative foot positioning in an x-directional standard crab gait. (a) Foot motion in the x–y plane; (b) Foot motion along the y-axis; (c) Foot motion along the x-axis.

moves on the sides of the supporting leg triangle. The standard stability margin s_0 is equivalent to half of a distance to be covered in T''' hours when a machine is walking at the speed of λ^* per T'' in Fig. 5, and is shown as

$$s_0 = \left(1 - \frac{3}{4\beta}\right)\lambda^*. \tag{3}$$

Taking account of this s_0 when determining the amount of shifting of the center of gravity is important as it provides the target of convergence configuration for the convergence-to-standard type gait.

The above study is restricted to the primary quadrant. The discussion can be expanded to any crab-walk gait of random crab-walk angle α, it needs only to re-define the moving range of the crab-walk using the amount of α corresponding to the critical crab-walk angle α_c as summarized in Table 1.

4.4. Predictive control

Real time processing of gait determination so as to choose the next leg to swing for a stride, to search for the landing position and to decide the shifting amount of the center of gravity, whilst checking them against the terrain information takes a certain amount of time. For this reason, if the next gait is to be determined just after a swung leg lands, some posed time is required upon every landing and, consequently, continuous and smooth walking is not realized. Accordingly, it is essential to introduce a predictive control system in which the gait-determining operation is conducted earlier than the actual walking motion and the gait command is quickly

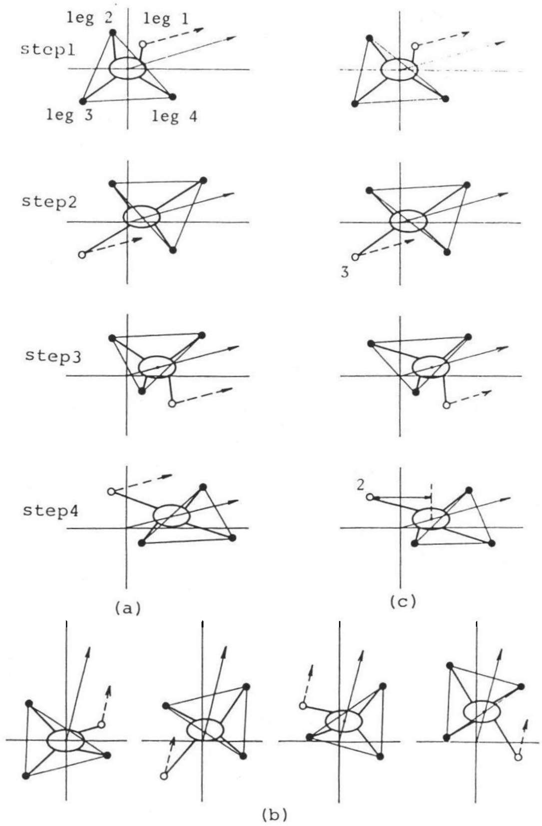

Figure 6. Crab walking leg sequence. (a) x-directional standard crab gait ($\alpha = 16°$); (b) y-directional standard crab gait ($\alpha = 74°$); (c) crab walking ($\alpha = 16°$) started from an arbitrary posture and swinging each leg by its maximum stride λ^*.

Table 1.
Re-definition of crab-walk angle α and motion range in omni-directional motion

Range of crab-walk angle α	Rotational angle of coordinates	Re-defined crab-walk angle	Re-defined motion range
		α'	$x'_0\ x^*\ y'_0\ y^*$
$-\alpha_c < \alpha \leq \alpha_c$	0	α	$x_0\ x^*\ y_0\ y^*$
$\alpha_c < \alpha \leq \pi - \alpha_c$	$\frac{\pi}{2}$	$\alpha - \frac{\pi}{2}$	$y_0\ y^*\ x_0\ x^*$
$\pi - \alpha_c < \alpha \leq \pi + \alpha_c$	π	$\alpha - \pi$	$x_0\ x^*\ y_0\ y^*$
$\pi + \alpha_c < \alpha \leq 2\pi - \alpha_c$	$\frac{3}{2}\pi$	$\alpha - \frac{3}{2}\pi$	$y_0\ y^*\ x_0\ x^*$

changed along with the walk. The predictive control system is classified into two levels depending on the advance degree of predetermination.

One is a long range terrain prediction by means of a visual sensor. The system modifies the moving direction of the center of gravity and moving velocity, etc, based on the information obtained by the sensor. This includes the function of Level B_I of the control system, to be explained in a later passage. However, this is not discussed in detail in this paper. Another is the prediction of the gait several steps ahead. The control system discussed in this paper focuses on the prediction of the gait one step ahead.

The present study assumes the following. The walking robot is executing the walking motion of the step S_k which ends the step-switching point N_k. Based on the gait pattern to be taken at N_k, the control system decides the gait to be taken at the next step S_{k+1} while executing the walk of S_k. In this way, the gaits to be taken later (steps ahead) are determined in advance. The moment when the robot reaches N_k, the computed next gait command is called to initiate the following step S_{k+1} so that the robot can walk continuously.

4.5. Irregularity-absorbing gait

A predictive control is premised that ensures a swung leg exactly lands on the position computed at the step-switching point N_k. If it lands at a different position, the predicted computer gait for the next step S_{k+1} cannot be used any more. On the other hand, land surfaces which look flat often have some irregularities. Therefore, the returning movements of swung legs require some up/down motions. These facts make it essential for predictive continuous walk to have a function to make the swung legs land on the computed xy coordinate position regardless of any irregularities. This function moves a swung leg up/down with some margin to absorb any minor irregularities of the land surface to ensure a smooth walk; It is called the 'irregularity-absorbing gait' hereinafter.

The irregularity-absorbing gait proposed in this paper assumes that a swung leg going down advances at the same speed as the supporting legs so that the swung leg descends vertically in the absolute coordinates. It is also assumed that both the ascending height h_{up} and descending height h_{dwn} are determined by the traversing ability on a surface which has a difference of altitude ΔH. In other words, a leg placed

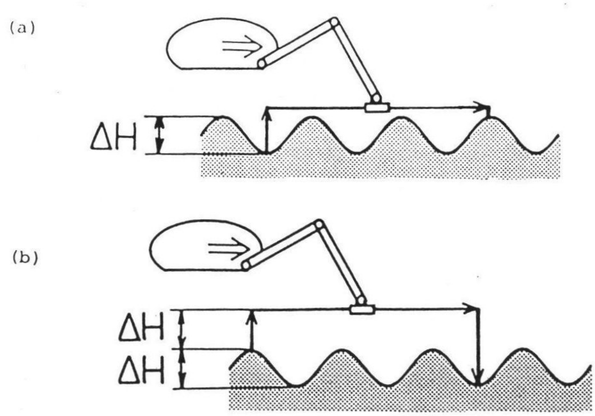

Figure 7. Swing leg trajectory which enables the absorbtion of unevenness ΔH of the terrain.

on a concave cannot make a returning motion without hitting a convex unless it lifts at least ΔH (Fig. 7(a)). A leg placed on a convex, if it lifts by ΔH at first, can reach a concave by lowering by $2\Delta H$ (Fig. 7(b)). On this account, h_{dwn} is tentatively set to be twice of h_{up}. This setting enables a swung leg to return even when a surface has maximum h_{up} of irregularities.

In summary, the irregularity-absorbing-gait proposed in this paper intends to make the trajectory of a swung leg at a body coordinates draw a form of an upside-down trapezoid as shown in Fig. 8(a). The trajectory is further sub-segmented to four phases of support, up, return and down. Where the support phase defined here, as stated in Section 5.2, exists only at the moment when the hind leg is going to swing. In this support phase, four leg advancing phase is, needless to say, generated. In general, the return motion of a swung leg is three-dimensionally independent of the direction of movement of the center of gravity. In such case, the trajectory of a swung leg is expressed as in Fig. 8(b,c).

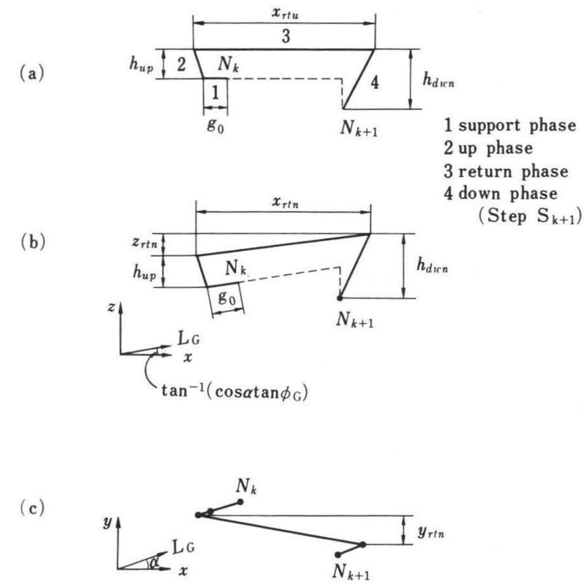

Figure 8. Three dimensional swing leg trajectory on body coordinates. (a) Special trajectory in case of $\alpha=\phi_G=0$; (b) side view of normal trajectory; (c) top view of normal trajectory.

The step-switching points N_k and N_{k+1} are determined as shown in Fig. 8. As stated previously, the step S_{k+1} is switched after waiting till the moment when the leg reaches N_{k+1} in the software, while the actual motion of the walking robot is assumed to stop at the moment when the tactile sensor detects the touch-down of the foot-tip in the leg descending, and consequently shifts to the four-leg advancing phase. In this manner, even with some increase/decrease of the four-leg advancing phase during walking, the standard stability margin s_0 is safely maintained above the prescribed value at the step-switching point to make the gait stable. In other words, the step-switching timing is unaffected by terrain, so that the robot can keep the standard gait and absorb the irregularities of the land surface.

4.6. Normal motion and emergent motion

Predictive walk implemented in the irregularity-absorbing-gait is called 'normal motion' in this paper. When the prediction is incomplete, however, the normal motion cannot be continued. In such cases, the robot has to tentatively discontinue normal motion and generate 'emergent motion'. The control system discussed in this paper is supposed to make a continuous walk based on the normal motion as much as possible, and will take the emergent motion only when the situation cannot be negotiated with the normal motion. In the emergent motion, the control makes the robot stop step by step.

5. *xy* GAIT DETERMINATION (LEVEL B_2)

This chapter discusses the gait-determining method on the xy coordinate plane for executing the convergence-to-standard gait transition in crab walk. The center of gravity is assumed to be at the step-switching point N_k. In the coordinate of E_k of the center of gravity: (1) xy coordinates: $P_i(x_i, y_i)$ of four legs ($i=1$–4), (2) crab-walk angle α, (3) duty factor β, and (4) reachable range of leg x^*, x_0, y^*, are used to obtain:

(i) leg u to be swung out,
(ii) shifting amount g_0 of the center of gravity on the xy plane when the swung leg u is in the support phase,
(iii) shifting amount g_u of the center of gravity on xy plane when the swung leg is in up, return and down phases,
(iv) swung leg landing position J_u,

until the next step-switching point N_{k+1}. The operation is executed in the order of: selection of swung leg, calculation of shifting amount of the center of gravity, setting the searching range of the swung-leg-landing position, calculation of the search-initiating position and the determination of the swung-leg-landing position. Each operation is explained in detail in the following sections.

5.1. Selection of the leg to swing next

The basic approach in selecting a leg to swing out next is as follows:

(1) If the plane layout of legs agrees even partly with the standard crab walk gait at the coordinate E_k of the center of gravity at N_k, a leg suitable for continuing the standard pattern is selected, without changing the pattern of their agreeing part.

(2) If none of them agree, a leg with the longest plane-returning distance ΔU is selected among the three legs other than the one which was swung in the preceding step S_k.

Such a selection method is one of the important factors for producing the convergence-to-standard type gait stated in Section 4.2, and reduces the inefficiency of determining the leg to swing after calculating the landing positions of all four legs. The specific algorithm is shown in Fig. 9. The signs of A, B, C and L in the figure are the parameters indicating the standard length among foot-tips in the standard crab-walk gait.

5.2. Determination of the shift of the centre of gravity

The shifting amount g_0 and g_u of the center of gravity at the step S_{k+1} are determined taking into account both the limits of the reachable range and the stability margin of

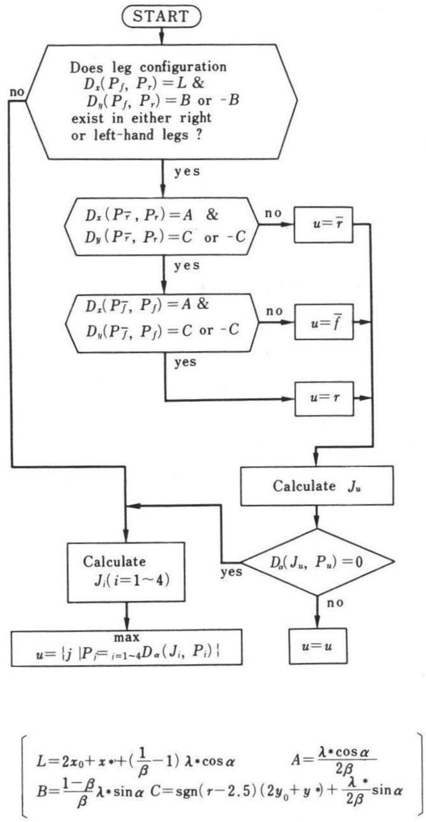

Figure 9. Swing-leg-selection algorithm.

the supporting leg(s) in the respective phase. As the preparation for the determination, the maximum horizontal shift distance g_{ix}, g_{iy} of the center of gravity, restricted by the reachable range of a leg i, is obtained when the leg i is touching the land during a walk at the crab-walk angle α. The equations are:

$$g_{ix} = (x_i - x_0)/\cos\alpha \qquad (i\text{: front leg}) \tag{4}$$

$$g_{ix} = (x_i + x_0 + x^*)/\cos\alpha \qquad (i\text{: hind leg}) \tag{5}$$

$\alpha > 0$

$$g_{iy} = (y_i - y_0)/\sin\alpha \qquad (i\text{: left leg}) \tag{6}$$

$$g_{iy} = (y_i + y_0 + y^*)/\sin\alpha \qquad (i\text{: right leg}) \tag{7}$$

$\alpha < 0$

$$g_{iy} = (y_i - y_0 - y^*)/\sin\alpha \qquad (i\text{: left leg}) \tag{8}$$

$$g_{iy} = (y_i + y_0)/\sin\alpha \qquad (i\text{: right leg}), \tag{9}$$

where, they are obtained using distance relations of a reachable area. In the case of equation (4), for instance, it is given by

$$D_x(P_i, P_{gix}) = x_0. \tag{10}$$

Using those values, the tolerable maximum horizontal shifting amount $g_{0\max}$ of the center of gravity when supported by four legs is obtained as follows:

$$g_{0\max}=\min(g_{ix},\ g_{iy}(i=1\text{–}4)) \tag{11}$$

and the tolerable maximum horizontal shift amount $g_{\max}$ of the center of gravity taking account of the reachable range of the three legs other than the swung leg is obtained from

$$g_{\max}=\min(g_{jx},\ g_{jy}(j=1\text{–}4:j\neq u)) \tag{12}$$

where, both $g_{0\max}$ and $g_{\max}$ may disregard g_{iy} and g_{jy} from the beginning when the crab angle $\alpha=0$.

In addition to $g_{0\max}$ and $g_{\max}$, if the standard stability margin s_0 is further taken into consideration, the horizontal distance g_0, g of the center of gravity when a robot is actually supported by four legs, and also in the subsequent phases, can be obtained. The calculation method should be different depending on which of the front/hind legs are to be swung out at the step S_{k+1}. The issue will be individually discussed here:

(a) When either front leg is swung out at the step S_{k+1}. Usually in this case, some domain of a supporting-leg-triangle at the step S_{k+1} is commonly shared by the same formed at the preceding step S_k, and the center of gravity is located inside the overlapping (common) domain. Therefore, a four-leg support is not required at the beginning of the step-switching point N_k. That is, $g_0=0$. On the other hand, the value of g is obtained as follows

$$\left.\begin{array}{lll}\text{(a)} & D_\alpha(X,\ P_G)<0 & \text{Cannot swing}\\ \text{(b)} & 0\leqslant D_\alpha(X,\ P_G)<s_0 & g=0\\ \text{(c)} & 0\leqslant D_\alpha(X,\ P_G)-s_0<g_{\max} & g=D_\alpha(X,\ P_G)-s_0\\ \text{(d)} & g_{\max}\leqslant D_\alpha(X,\ \mathrm{P}_G)-s_0 & g=g_{\max}\end{array}\right\}. \tag{13}$$

Here, X is the intersection of a straight line $L(P_{\bar{f}},\ P_r)$ connecting a leg $\bar{f}$ with r, and the trajectory L_G of the center of gravity, defined relative to the front swing leg.

(b) When either hind leg is swung out at the step S_{k+1}. When either hind leg swings, a supporting-leg-triangle at the step S_k and the same at the step S_{k+1} adjoin each other at the line $L(P_{\bar{r}},\ P_f)$. Accordingly, at the beginning of the step S_{k+1} which tries to take finite standard stability margin s_0 essentially requires the four-leg-support phase. It means that the support phase is indispensable at the beginning of the swing of a hind leg. In this case, the shift amount g_0 of the center of gravity in the support phase is obtained as follows

$$\left.\begin{array}{lll}\text{(a)} & g_{0\max}\leqslant D_\alpha(X,\ P_G) & \text{Cannot swing}\\ \text{(b)} & g_{0\max}\leqslant D_\alpha(X,\ P_G)+s_0<g_{0\max}+s_0 & \\ & & g_0=g_{0\max}\\ \text{(c)} & 0\leqslant D_\alpha(X,\ P_G)+s_0<g_{0\max} & g_0=D_\alpha(X,\ P_G)+s_0\\ \text{(d)} & D_\alpha(X,\ P_G)+s_0\leqslant 0 & g_0=0\end{array}\right\}. \tag{14}$$

Here, X is the intersection of $L(P_{\bar{r}},\ P_f)$ and L_G. Equation (14) intends to obtain the completion time of the swung-leg support phase in a manner to agree, as much as possible, with the moment when the center of gravity enters, by the standard stability margin s_0, into the supporting-leg-triangle at the step S_{k+1}. The center of gravity should advance as much as possible if it can be inside the supporting-leg-triangle of the step S_{k+1}. Therefore, $g=g_{\max}$.

The above equations produce the methods of determination of g_0 and g. The shift amount g_u of the center of gravity after the swung leg shifts to the up phase as far as N_{k+1} is naturally, $g_u=g-g_0$.

5.3. Prescribing methods of the domain of searching for the swung-leg-landing position
After determining the swung-leg u at the step S_{k+1} and obtaining the shift distance g of the center of gravity in the coordinate E_k, it is necessary to prescribe the searching domain for determining the swung-leg-landing position of N_{k+1} at the coordinate E_k. The simplest approach will be to set the whole reachable range u as the domain (as a matter of course, it is an imaginary reachable range in the software already defined). However, simulative operation demonstrated this approach to be unrealistic. For instance, the problem is found as illustrated in Fig. 6. Fig. 6(a) is the x-directional standard crab-walking gait. Assume it starts from a somewhat different pattern, such as Fig. 6(c), and the swung legs make a return motion as much as in the reachable range. Consequently, the robot falls into a non-walkable state at the fourth step. It cannot walk even when the land surface is perfectly flat. This finding obviously makes it essential to restrict the landing position of the swung leg.

The results of many simulation analyses suggest three kinds of approach in the prescription method. They are named the domain-prescribing methods I, II and III.

5.3.1. Domain-prescribing method I. Why does the walk become impossible at the fourth step in Fig. 6(c)? Because step 2 cannot swing since the center of gravity cannot enter the supporting triangle laying ahead. This is even the case when leg 2 stretches to a maximum at the moment of swing. However, this problem already occurred when the leg 3 landed two steps earlier. The above-stated problem must have been avoided if proper consideration was made, when determining the landing position of leg 3, about the limit of the reachable range of leg 2 which was to come after two steps. This consideration is the basis of the domain-prescribing method I.

The domain-prescribing method I is applicable only to determining the landing domain of the hind legs. At this time, the reachable ranges should be considered for the swung leg u itself and $\bar{f}$ and $\bar{r}$ other than the front leg f relative to the swung leg u. In the normal sequence, a front leg f swings at the step S_{k+2} after a certain hind leg u swung at the step S_{k+1}. Method I intends to restrict the searching domain of step S_{k+1} beforehand so as to avoid the state where the center of gravity cannot enter the supporting-leg-triangle at the following step S_{k+3}. The procedure is specifically presented next.

At first, the reachable range of a swung leg to be considered is assumed to be the projection of the range on the coordinate E_{k+1} to the coordinate E_k. This reachable range is further restricted as follows:

(1) At first, restriction of legs $\bar{f}$ and $\bar{r}$ only is considered relative to a swung leg u. In this case, the horizontal shift amount $g_{\max'}$ of the center of gravity cannot be larger than the minimum values of the restriction of the respective xy-directional reachable ranges, i.e.

$$g_{\max'} = \min(g_{\bar{f}x}, g_{\bar{f}y}, g_{\bar{r}x}, g_{\bar{r}y}) \tag{15}$$

Therefore, the domain to be searched is behind $L(P_{g_{\max'}}, P_{\bar{f}})$. In this setup, even with both legs $\bar{f}$ and $\bar{r}$ still resting on land after two steps, the center of gravity can pass the straight line $L(P_{\bar{f}}, P_{\bar{r}})$ and remain within the supporting-leg-triangle ($\Delta\bar{f}fu$), at least with the longitudinal stability margin $s=0$. An example of the prescribed domain for leg 3 is shown as the straight line I in Fig. 10.

(2) Next, the restriction by leg u itself is studied. Depending on the landing position, leg u can also inhibit, after two steps, the motion to carry the center of

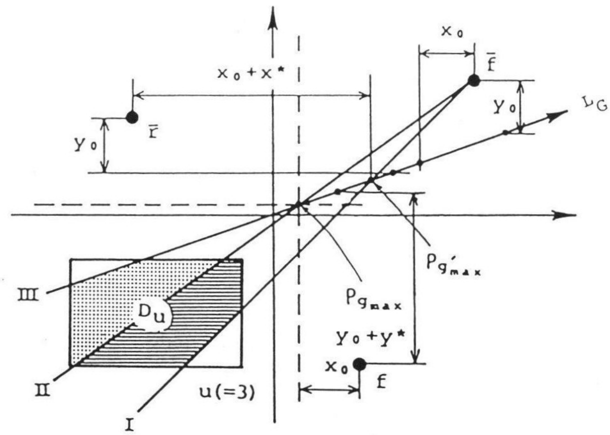

Figure 10. Illustration of a part of the domain prescribing method I, II and III.

gravity forward on a diagonal line between legs u and f. The calculation of this limiting domain is a little complicated. The first assumption is the situation shown in Fig. 11, in which the swung leg u is leg 3, and is going to land on any of $x=x_3$. G_0 is set to satisfy

$$D_x(G_0, P_3)=x_0+x^* \tag{16}$$

on the body motion trace L_G. At this time, leg 3 should be behind the line $L(P_1, G_0)$ connecting P_1 with G_0. This setup enables, after two steps, the center of gravity to be positioned ahead of the line connecting swung leg u with leg P_1 when arriving at G_0. This condition tolerates a segment up to $y=0$–P_c on the line of $x=x_3$ against the intersection P_c of $L(P_1, G_0)$ and $x=x_3$. When the line x_3 which indicates such domain is changed, the point $P_c(x_c, y_c)$ produces a hyperbola as follows and the tolerable range exists on the side of its origin.

$$(y-x \tan \alpha)(x-x_f+\mathrm{d}x_u)=(y_f-x_f \tan \alpha)\mathrm{d}x_u \tag{17}$$

where, $\mathrm{d}x_u=x_0+x^*$. When the same principle is applied to the y-directional reachable range, the critical line is:

$$(y-x \tan \alpha)(y-y_f+\mathrm{d}y_u)=(y_f-x_f \tan \alpha)\mathrm{d}y_u, \tag{18}$$

where,

$$\mathrm{d}y_u=\begin{cases} -y_0 & (\alpha>0 \quad \text{Leg 2}) \\ -y_0-y^* & (\alpha<0 \quad \text{Leg 2}) \\ y_0+y^* & (\alpha>0 \quad \text{Leg 3}) \\ y_0 & (\alpha<0 \quad \text{Leg 3}) \end{cases}$$

The tolerable domain is also on the side of the origin. The domain-prescribing method I is the common domain shown by the three limiting lines.

5.3.2. Domain-prescribing method II. This method is also applicable to the hind legs only just as Domain prescribing method I. But, to be studied is the convergence at the step directly after and not two steps after. During the leg-swinging sequence in the standard gait it occurs that after a hind leg u is swung at the step S_{k+1}, the front leg

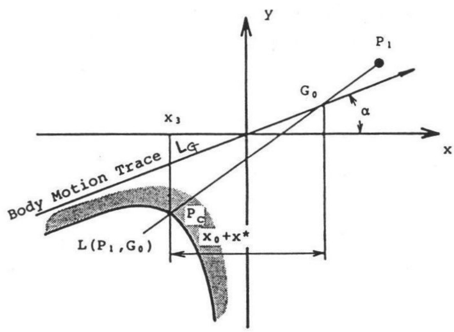

Figure 11. Loci of the point P_c in domain-prescribing-method I, based on the geometric limitation of leg u.

f swings at the step S_{k+2}. This is desirable and should always try to realize this order even in free gait so as to make prompt convergence to the standard gait. Accordingly, method II insists that a swung leg u should be placed ahead of $L(P_f, Pg_{max})$ (where g_{max} is the shift amount of the center of gravity at the step S_{k+1} as defined in equation (12)).

Whilst method II does not completely prohibit landing on any domain other than that designated, it only provides priority order for searching. This is obviously different from the case of method I.

5.3.3. Domain-prescribing method III. This method is simple and is applicable to front legs as well as hind legs. For instance, as shown in Fig. 10, it searches only the right-hand side of the body motion trace L_G for leg 3 when L_G crosses the leg's reachable range owing to large crab-walk angle α. It is aimed at maintaining the left/right relations of the leg with L_G.

The domain of searching for swing leg landing position D_u of a swung leg u satisfies those domain-prescribing-methods I, II and III and is defined as the domain within the leg's reachable range. Figure 12 presents the application of the domain-prescribing methods quoting the walking case on H-type terrain.

5.4. Determining search-initiating point I_u

The reason for focusing on the search-initiating point I_u within a searching domain D_u is that I_u automatically becomes the landing position J_u on a flat land and O-type rough terrain. Therefore, this selection provides the convergence characteristic to the convergence-to-standard type free gait. For determining I_u, a 'phase-maintaining method' is proposed. This method focuses attention on the position of a leg (tentatively called u^*) which is a swung leg one step ahead of a leg u in the standard gait. The leg u^* is assumed, being in the supported phase, to reach the boundary of the reachable range in either the x or y direction. At this time, the swung leg u is assumed to be on the standard stroke trajectory of the foot-tip (see Fig. 4), and it is located ahead of u^* as much as the phase difference to be taken in the standard gait from this course-end (intersection with the reachable range boundary). The leg u arrives at the course-end when leg u^* completes the returning motion. Provided the return-completing point of u^* is the course-starting point of the standard gait, the positional relation between u and u^* agrees with the pattern of the standard gait. In this way, the authors intend to determine I_u, which has the characteristics of high convergence to the standard gait. Specifically, points $P_{\Delta x}$, $P_{\Delta y}$ are obtained on the standard stroke trajectory of the foot-tip. They should satisfy

$$\left.\begin{aligned} D_x(P_{\Delta x}, P_{u*})=\Delta x \\ D_y(P_{\Delta y}, P_{u*})=\Delta y \end{aligned}\right\}. \tag{21}$$

Δx, Δy are shown on Table 2. I_u should be the one having smaller returning amount of swung leg of $P_{\Delta x}$ and $P_{\Delta y}$. If both are not included in the searching domain D_u, I_u should be the forward one of the intersections of foot-tip standard stroke trajectory and D_u boundary. This is the 'phase-maintaining method' proposed by this paper.

Table 2.
Δy and Δy for the phase-reserved positioning method

u	$u*$	Δx	Δy
1 4	2 3	$2x_0+\frac{3}{2}x^*+\left(\frac{1}{\beta}-\frac{3}{2}\right)\lambda^*\cos\alpha$	$\frac{\mathrm{sgn}(\alpha)}{2}y^*+\left(\frac{1}{\beta}-\frac{3}{2}\right)\lambda^*\sin\alpha$
2 3	4 1	$-2x_0-\frac{1}{2}x^*-\frac{1-\beta}{2\beta}\lambda^*\cos\alpha$	$-\mathrm{sgn}(u-2.5)\cdot(2y_0+y^*)$ $+\frac{\mathrm{sgn}(\alpha)}{2}y^*-\frac{1-\beta}{2\beta}\lambda^*\sin\alpha$

I_u could be determined by other approaches based on the standard position relative to the center of gravity and positional inter-relationships among the legs. However, simulation has demonstrated this 'phase-maintaining method' was best in terms of convergence to the standard pattern.

5.5. Determining the landing position J_u

Several approaches are possible in order to determine the actual landing position J_u which starts from the search-initiating point I_u within the searching domain D_u. The authors would like to propose a rather simple method.

1. The searching domain D_u is divided, using map information, into independent cells a_{ij} each having a finite width.
2. The cell a_{ij} in which the search-initiating point I_u exists is checked against the map and it is determined if the place is not a hole and if it is possible to land on. If possible, the point, is set as the landing position. If impossible step 3 is taken.
3. In the direction of the row, cells within D_u are checked for landing-possibility as in the order of $a_{i+1,j}$, $a_{i-1,j}$, $a_{i+2,j}$, $a_{i-2,j}\ldots$
4. If suitable landing positions are not found, the search is expanded to the column direction as $j-1, j+1, j-2, j+2\ldots$ within the domain D_u to ultimately determine J_u. In this case, the search starts at each column from the cell containing the foot-tip standard stroke trajectory.

5.6. Investigation by computer simulation

The effectiveness of the introduced gait-determining method is checked by various computer simulations. Three cases are presented here.

Figure 12 specifically presents the gait-determining sequence on H-type terrain. It

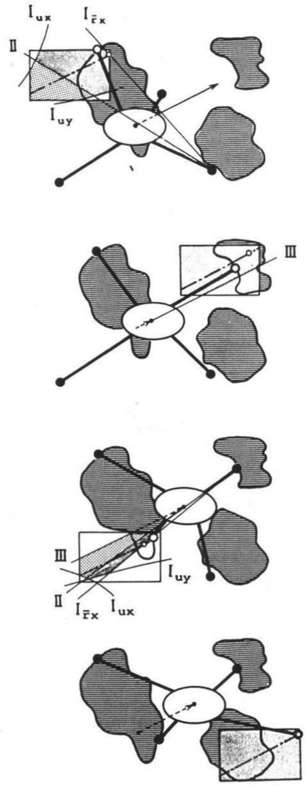

Figure 12. Integrated procedure of the adaptive-gait-control sequence $\alpha=28°$; $\beta=0.8$; I_{rx} indicates the domain prescribing method I when the x-directional mechanical limit of leg r is applied.

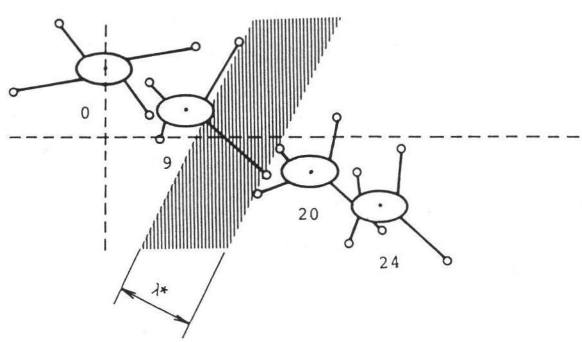

Figure 13. Walking motion over a river using the proposed algorithm (step numbers are shown: $\beta=0.75$).

shows how domain-prescribing-methods I, II and III are executed and D_u, I_u and J_u are set.

Figure 13 is a simulation of a robot crossing over an obstacle equivalent to a river. The river width λ^* is assumed to be the same as the maximum swinging width of the leg tolerable within the reachable range. The figure shows the robot takes, at the foreground of the river, the special setup for crossing the river and automatically goes back, after crossing over, to the standard crab-walk gait.

Figure 14 is a walk over H-type terrain having many concaves. Although a course is dictated by Level A, the course has large holes which are untraversable for the robot. Accordingly, the gait-determining system bypasses the obstacle in a trapezoid configuration and keeps on walking by continually changing the crab-walking angles. Such a bypassing trajectory is generated at Level B_1. Although the generating method is not discussed in this paper, whose simulations prove that the convergence-to-standard type gait is generated based on the gait-determining methods proposed by this study. This is true even on considerably rough terrain, so that the robot continues the walk tracing the commanded body motion trajectory.

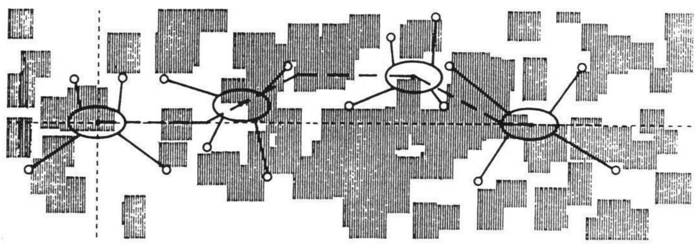

Figure 14. Adaptive walking on *H*-type terrain with local modification of the motion trace.

6. DETERMINATION OF z GAIT (LEVEL B_3)

The preceding Section clarified the methods used to obtain the position $P_g(g \cos \alpha, g \sin \alpha)$ of the center of gravity on step-switching point N_{k+1} and the position of the swung leg $J_u(x_u, y_u)$ in the coordinates E_k. This chapter presents the methods to obtain the respective heights g_z, z_u.

The height z_u of a swung leg is not difficult to calculate as it can be obtained by selecting the height on the map on the coordinate E_k corresponding to the swung-leg-landing point $J_u(x_u, y_u)$.

To calculate the center of gravity's height g_z, it is necessary to take into account the conditions to maintain the center of gravity at the height H from the surface and the conditions to continuously move the torso up and down in order to prevent it from hitting the land. While several approaches are possible to obtain g_z, the present study proposes a technique making use of the height information of the front legs $(f, \bar{f})$ only. Here the name 'front' is defined relative to the crab-walk angle.

In a walking machine, the front legs are generally positioned ahead of the center of gravity in the advancing direction. This makes if possible to predict the height of the terrain laying ahead for the center of gravity based on the height of front-leg-landing position. Therefore, this technique initially obtains the heights from the landing surface of the two front legs at an estimated N_{k+1} by checking against the map. An intersection of the straight line $L(P_f, P_{\bar{f}})$ connecting the two front legs on the xy-plane with the center of gravity's trajectory L_G is set to be $A(x_A, y_A)$, and the predicted height of the point A is:

$$\hat{z}_A = \frac{(x_A - x_{\bar{f}})z_f + (x_f - x_A)z_{\bar{f}}}{x_f - x_{\bar{f}}}. \tag{20}$$

It is not a good method to predict the latitude of the point A only from the map information without resorting to a calculation based on the above-stated equation. For instance, when a hole is to be crossed over, the calculation disregarding equation (20) cannot neglect the depth of the hole.

After determining the predicted height of point A, the center of gravity's height at point A is determined by $\hat{z}_A + H$. Consequently, the target value g_z at the center of gravity's height at N_{k+1} is

$$g_z = \frac{g}{\sqrt{x_A^2 + y_A^2}}(\hat{z}_A + H). \tag{21}$$

In the actual control, the upper and lower limits are set taking account of z-directional reachable range as, $z_g = -z_0$ when $z_g \geqslant -z_0$ and $z_g = -z_0 - z^*$ when $z_g \leqslant z_0 - z^*$. (The reachable range in this case is set to be $-z_0 - z^* \sim -z_0$ regarding the ascending height of swung leg is contained in the upper margin δz.) In this way, the angle of elevation ϕ_G of the center of gravity in the moving direction at the step S_{k+1} is $\phi_G = \tan^{-1}(g_z/g)$.

Thus, the technique currently proposed predicts the center of gravity's heights at first, and then, controls the center of gravity's heights by linking the first-obtained heights linearly. A simulation based on this technique is shown in Fig. 15. In this figure, the broken line shows the trajectory produced by the conventional method in which the average height of the supporting legs is constantly set as H. It indicates that the present method, based on prediction, can control the center of gravity's height in a much improved and far more smooth manner. The study assumes that the center of gravity is kept sufficiently high and does not investigate a case when the torso's lower edge makes contact with the ground surface.

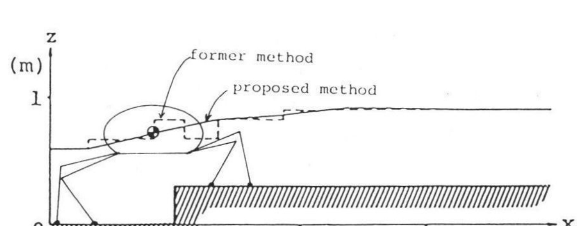

Figure 15. The trajectory of body's center over steps.

7. GENERATION OF LEG TRAJECTORY (LEVEL B_4)

So far the calculation methods for the center of gravity P_g and swung-leg-position J_u at the step-switching point N_{k+1} in the coordinate E_k have been presented. Those procedures have completed the preparation for calculating the velocity-commanding-values to the whole four-leg-driving servo system at the step S_{k+1}. The calculation methods are next presented in classification of the cases of the supporting and swung legs. As a premise at this stage of discussion, the center of gravity's moving velocity v_G is assumed to be constant at every step. This is assumed because of the simplicity of the calculation, although a continuous change of velocity from step to step should be taken into consideration for the improved smoothness of the walk in the future.

Supporting legs swing synchronously in the opposite direction of the motion of the center of gravity. Accordingly, their x-, y- and z-directional shifting distance are known as $(-g\cdot\cos\alpha, -g\cdot\sin\alpha, -g_z)$ across the board. However, the velocity $-v_G(-v_{Gx}, -v_{Gy}, -v_{Gz})$ is determined after calculating the velocity of the swung leg based on the constant velocity condition of the body.

The motion of swinging legs premises, as previously stated, that the robot takes an irregularity-absorbing gait which includes the up/down motion of the leg. Its specific calculation is a little complicated. The following section presents the specific calculation method of such an irregularity-absorbing gait and subsequently discusses a method to generate the trajectory-reference value for all legs including those which are swinging.

7.1. Leg trajectory generation for an irregularity-absorbing gait

As previously stated, in order to execute the irregularity-absorbing gait, a swung leg should be able to implement a three-dimensional return motion consisting of four phases of support, up, return and down, in coordination with the thrusting motion of other supporting legs at the step S_{k+1}. The center of gravity's shift distance in the support phase is given to be g_0 by the analysis of Section 5.2. The control in the support phase is the same as the supporting leg. Therefore, the conditions are only discussed for the three phases of up, return and down. Here again, the x-directional relations are initially calculated.

The known values for the calculation are the center of gravity's x-directional shifting amount g_{ux} $(=g_u\cdot\cos\alpha)$ during the three phases obtained at the gait determination in Levels B_2 and B_3; the swung-leg's x-directional returning distance $D_x(J_u, P_u)$ in the coordinate E_k; the swung-leg's up/down height h_{up}, h_{dwn}, assumed to be defined based on the measurements of the terrain; and the up/down motion's velocities v_{up}, v_{dwn}, which are usually set to be the mechanically available maximum values to produce high speed walk. On the other hand, the leg trajectory parameters that are to be obtained are the center of gravity's x-directional shifting velocity v_{Gx} relative to the land surface; the swung-leg's x-directional returning velocity v^x_{rtn} relative to the center of gravity; and the swung-leg's returning distance x_{rtn} relative to the center of gravity. The following relations should hold for them;

$$g_{ux}=v_{Gx}\left(\frac{h_{\mathrm{up}}}{v_{\mathrm{up}}}+\frac{x_{\mathrm{rtn}}}{v^x_{\mathrm{rtn}}}+\frac{h_{\mathrm{dwn}}}{v_{\mathrm{dwn}}}\right) \tag{22}$$

$$D_x(J_u, P_u)=x_{\mathrm{rtn}}+v_{Gx}\left(\frac{x_{rtn}}{v^x_{\mathrm{rtn}}}\right). \tag{23}$$

Equation (22) represents that the center of gravity's shifting amount g_{ux} in the up, return and down phases is same as its shifting amount when it advances at the velocity v_{Gx} in the said three phases. Equation (23) indicates a relation that swung-leg's returning distance on the coordinate E_k is the sum of its returning distance x_{rtn} relative to the center of gravity and the centre of gravity's shifting amount in the return phase.

The authors would like to solve these two equations to obtain the three parameters of the leg trajectory, v_{Gx}, v^x_{rtn} and x_{rtn}, but, one unknown parameter should be defined at first. The unknown parameters are set as follows, depending on the situation.

(1) The x-directional swung-leg's returning velocity v^x_{rtn} is set to be the mechanically available maximum velocity V_x. This premise is given when the maximum velocity of the center of gravity V_{Gx} is required. In this case, the value of V_{Gx} is:

$$V_{Gx}=\frac{\sqrt{B^2-4\,AC}-B}{2A} \tag{24}$$

where,

$$\text{where,}\quad \begin{cases} A=\left(\dfrac{h_{\mathrm{up}}}{v_{\mathrm{up}}}+\dfrac{h_{\mathrm{dwn}}}{v_{\mathrm{dwn}}}\right)\Big/\ V_x \\ B=\dfrac{h_{\mathrm{up}}}{v_{\mathrm{up}}}+\dfrac{D_x(J_u,P_u)-g_x}{V_x}+\dfrac{h_{\mathrm{dwn}}}{v_{\mathrm{dwn}}} \\ C=-g_{ux} \end{cases}$$

At this time, x_{rtn} is obtained as follows:

$$x_{\mathrm{rtn}}=V_x\left\{\frac{g_{ux}}{V_{Gx}}-\left(\frac{h_{\mathrm{up}}}{v_{\mathrm{up}}}+\frac{h_{\mathrm{dwn}}}{v_{\mathrm{dwn}}}\right)\right\}. \tag{25}$$

(2) The center of gravity's velocity is set to be v_{Gx}, which means the robot is moving at a desired speed of v_{Gx} slower than the maximum speed of V_{Gx} obtained in the preceding (1). In this situation, x_{rtn} and v^x_{rtn} are obtained as follows:

$$x_{\mathrm{rtn}}=(D_x(J_u,P_u)-g_x)+v_{Gx}\left(\frac{h_{\mathrm{up}}}{v_{\mathrm{up}}}+\frac{h_{\mathrm{dwn}}}{v_{\mathrm{dwn}}}\right) \tag{26}$$

$$v^x_{\mathrm{rtn}}=\frac{x_{\mathrm{rtn}}}{\dfrac{g_{ux}}{v_{Gx}}-\left(\dfrac{h_{\mathrm{up}}}{v_{\mathrm{up}}}+\dfrac{h_{\mathrm{dwn}}}{v_{\mathrm{dwn}}}\right)}. \tag{27}$$

Now, (1) and (2) clarify the method to determine the walking parameters for a robot to move at a desired speed of v_{Gx} slower than the center of gravity's maximum speed V_{Gx} whilst executing the irregularity-absorbing gait.

The above discussion only concerns the x-directional relations. Similar equations can hold for the y and z directions. When the crab-walking angle α and angle of elevation ϕ_G are negative, the center of gravity's shifting amount is negative during the return of the swung leg. In this situation, after changing the sign, the walking parameters are calculated and subsequently, the sign is restored. Should this procedure be assumed, the above stated discussion holds true.

The return motion of the swung leg should be synchronized in the x-, y- and z-directions. On this account, even when the higher level (Level A) commands v^d_G, the center of gravity's velocity v_G is restricted in its upper limit by the x-, y- and z-directional maximum velocities V_{Gx}, V_{Gy} and V_{Gz}. Actually, it should be

$$v_G=\min\left(\frac{V_{Gx}}{\cos\phi_G\cos\alpha},\ \frac{V_{Gy}}{\cos\phi_G\sin\alpha},\ \frac{V_{Gz}}{\sin\phi_G},\ v^d_G\right). \tag{28}$$

In this case, the swung-leg's time t_{rtn} in the return phase is

$$t_{\text{rtn}} = \frac{g_u}{v_G \cos \phi_G} - \left(\frac{h_{\text{up}}}{v_{\text{up}}} + \frac{h_{\text{dwn}}}{v_{\text{dwn}}} \right). \tag{29}$$

The above equations clarify the methods used to calculate the time t_{rtn} and the center of gravity's shifting velocity v_G in the return phase taking account of xyz synchronization. In this case, the center of gravity moves in the x-direction at the velocity

$$v_{Gx} = v_G \cdot \cos \phi_G \cos \alpha, \tag{30}$$

and $v_{Gy} = v_G \cos \phi_G \sin \alpha$, $v_{Gz} = v_G \sin \phi_G$.

The x-directional speed in the return phase is

$$v^x_{\text{rtn}} = (D_x(J_u, P_u) - g_x)/t_{\text{rtn}}, \tag{31}$$

$t_{\text{up}} = (h_{\text{up}}/v_{\text{up}})$, $t_{\text{dwn}} = (h_{\text{dwn}}/v_{\text{dwn}})$ are self-explanatory.

The time t_{spt} in the support phase at the beginning of the swing of any hind leg is

$$t_{\text{spt}} = g_0/(v_G \cdot \cos \phi_G). \tag{32}$$

The step time T_{k+1} of the step S_{k+1} is

$$T_{k+1} = t_{\text{spt}} + t_{\text{up}} + t_{\text{rtn}} + t_{\text{dwn}}.$$

Thus, all the unknown parameters of the trajectory are obtained and all the command values for the driving servo system are produced.

8. REFLEX MOTION REGULATION SYSTEM (LEVEL C)

Level C is the motion-regulation sub-system, executed during the sampling times of specified intervals segmenting each step. During the sampling times the position-monitoring signals from the leg-driving servo system; the signals from tactile sensors at the foot-tips and torso, and the signals from the posture sensors are firstly received. The leg-servo commands calculated beforehand at Level B are then modified with the emergent evasive-motion-commands and maintain stability commands. The modified commands are finally provided to the twelve leg-driving servos as the command values. Level C is the sub-system to repeat such a cycle. The sampling time should be as short as possible in relation to the operation speed of the processor in order to produce high speed and smooth motion of the legs. For instance, at 1 m/s of the leg-swing speed, the leg moves 50 mm in the sampling time of 50 ms. But, this is insufficient to control the adjustment of the legs' speed or to cope quickly with obstacles. Therefore, the minimization of the sampling time is one of the important factors in the consideration of the Level C processing system. Besides, at Level C a control system much depends on the characteristic of hardware of the walking machine. The current study develops a discussion based on the experimental robot TITAN III (to be presented in a later section). The control algorithm at Level C is hereinafter explained. The explanation concerns the processing procedure at the nth sample time in the step S_k during a walk.

(1) At the sampling-initiating point ($n\Delta t$), Level C takes in potentiometer signals concerning the position of the four legs $p_i(x_i, y_i, z_i)$ ($i = 1$–4), tactile signals from each

leg, posture signals for pitching angle and rolling angle, and command signals for crab-walk angle and moving speed from the joystick.

(2) The leg-trajectory-producing algorithm is used for a swung leg. Command values of a swung-leg at the time $t(n\Delta t \leq t < (n+1)\Delta t)$ are given as:

$$\left.\begin{aligned} x_u^d(t) &= x_u^d((n-1)\Delta t) + v_{ux}\Delta t \\ y_u^d(t) &= y_u^d((n-1)\Delta t) + v_{uy}\Delta t \\ z_u^d(t) &= z_u^d((n-1)\Delta t) + v_{uz}\Delta t \end{aligned}\right\} \tag{33}$$

in order to trace the trajectory in the up, return and down phases. Where, Δt is a sampling interval, and v_{ux}, v_{uy} and v_{uz} are the velocities as defined in Table 3 for the individual phases. v^* on the Table is set to be same as the velocity commands for the supporting leg. $x_u^d(0)$, $y_u^d(0)$ and $z_u^d(0)$ correspond to the coordinates of the swung-leg positions at the step-switching point N_{k-1}.

Table 3.
Velocity commands in swing leg phases

phase / v_u	support	up	return	down
v_{ux}	$-v_{Gx}$	$-v_{Gx}$	v_{rtn}^x	$-v_{Gx}$
v_{uy}	$-v_{Gy}$	$-v_{Gy}$	v_{rtn}^y	$-v_{Gy}$
v_{uz}	v^* (note)	v_{up}	v_{rtn}^z	v_{dwn}

(3) The supporting leg is set as:

$$x_j^d(t) = x_j^d((n-1)\Delta t) + v\Delta t \tag{34}$$

$$y_j^d(t) = y_j^d((n-1)\Delta t) + v\Delta t \tag{35}$$

$$\begin{aligned} z_j^d(t) = &\{z_j^m(n\Delta t) + (z_j^*(n\Delta t) - \bar{z}_j^m(n\Delta t))\} \\ &+ C_1(-x_j^m(n\Delta t)\cdot\theta_p + y_j^m(n\Delta t)\cdot\theta_r) \\ &+ C_2\Delta z \end{aligned} \tag{36}$$

In the xy directions, the command values are merely varied at a prescribed speed, while in the z direction, several adjusting functions are added. That is, the $z_j^*(n\Delta t)$ in the right hand first term of the equation (36) is defined as:

$$z_j^*(n\Delta t) = \begin{cases} \bar{z}_j^m(0) & n=0 \\ z_j^*((n-1)\Delta t) - v_{Gz}\Delta t & n\geq 1 \end{cases} \tag{37}$$

It is the height command value which is unaffected by both posture and pliancy controls. $\bar{z}_j^m(n\Delta t)$ is the average monitored value of supporting-leg-heights. Therefore, the right hand first term of equation (36) adjusts the average height of the center of gravity.

The $x_j^m(n\Delta t)$ and $y_j^m(n\Delta t)$ values in the right hand second term of equation (36) are the monitor values of the supporting-leg coordinates at the time $n\Delta t$, and θ_p and θ_r are the deviations of the rolling and pitching angles from the horizontal plane at each sampling time. Accordingly, this second term generates the posture-modifying-command values.

The Δz value of the right hand third term in equation (36) is for the motion which extends a leg downward by a certain length when the sole sensor of the leg turns OFF in the four-leg support phase. The four-leg support generates a statistically indeterminant condition. Therefore this adjusting function is necessary for supporting the body weight with four legs as much as possible. On this account, the function of Δz is named 'pliancy control'. C_1 and C_2 are the weighting index to give sensitivities of posture and pliancy controls.

(4) The difference between the calculated $x_i^d(t)$, $y_i^d(t)$ and $z_i^d(t)$ and actual monitor values of the legs detected at the time $n\Delta$t leads to the generation of the speed commands to the servo system at a time t as follows

$$\left.\begin{aligned} v_{ix}^d(t) &= (x_i^d(t) - x_i^m(n\Delta t))/\Delta t \\ v_{iy}^d(t) &= (y_i^d(t) - y_i^m(n\Delta t))/\Delta t \\ v_{iz}^d(t) &= (z_i^d(t) - z_i^m(n\Delta t))/\Delta t \end{aligned}\right\}. \tag{38}$$

In addition to the P control for the generation of the speed command values, PID control appropriate for a walking robot should be introduced in the future. The issue is still too early for the current study. The above summarizes the operation of Level C.

In equation (33), a moving-distance-calculation method such as $x_i(n\Delta t) = x_i(0) + n\Delta x$ is not employed because rewriting the initial value $x_i(0)$ at every change of step makes the procedure too complicated. The method of equation (33) can control, in the same and simple procedure, four legs having different step phases and can execute the operation quickly. The error accumulation can be eliminated at every cycle so that any minor error can be considered negligible.

9. EMERGENT MOTIONS AND CONTROL THEREOF

9.1. Kinds of emergent motions

Emergent motions are taken when the normal motions, based on the predictive control, cannot work. At present, three kinds of emergent motions are conceived.

(1) When a swung leg touches an obstacle during walking.
(2) When a swung leg does not touch the ground at reaching a step-switching point.
(3) When the foothold at a landing position for a swung leg is instable.

Properly speaking, (1) should include the case that the torso hits an obstacle. Nevertheless, the case is tentatively omitted as the processing method can be devised corresponding to the cases of legs, and the current study assumes the torso being held relatively high. The processing procedure for (1), (2) and (3) are summarized in the following section.

9.2. Processing procedure for emergent motions

In the emergent motion in the case of (1), when signals are input from the sensor of a swung-leg foot-tip, the control system (a) immediately stops the advancing motions of the swung leg and torso and puts the swung leg into the emergent motion, which track the returning trajectory of the swung leg and lift it by certain amount; and then (b) makes the swung leg go back at somewhat lower velocity while the other supporting legs stand still; (c) as the result of (b), if the swung leg hits any obstacle again, a proximity-sensor works to lift the leg and holds it some distance from the obstacle; (d) if the leg does not touch any obstacle in the action of (b), the leg is allowed to restore normal motion; (e) if the leg crosses over the obstacle, it is also allowed to restore normal motion; (f) if the leg still cannot over-ride the obstacle in the action of (c), the system goes back to the Level B, in which the landing position is searched again by the following procedure:

(1) By analyzing the emergent motion, the position of the obstacle is judged and designated to be a prohibited domain on the map.
(2) The current position of the swung leg is set to be the landing-position-search-initiating point, from which new landing positions, including backward walk, are determined.
(3) Subsequently, the normal motion is restored.

In the emergent motion in case (2), the torso stops advancing immediately and the swung leg descends vertically. If the leg does not touch the ground, even at reaching the lower reachable range, the position is written in the map as landing-prohibition, and landing positions are searched again using the same procedure as in (1).

The case of (3) is like tripping at the edge of a stairway. When such instable ground is detected by the sensor at the foot-tip, the landing positions are searched again in the same manner as (1). If the foot-tip sensor group can read the direction of the edge, the prohibition domain to be written in the map can be shaped as a rectangle having such a direction.

The experimental robot TITAN III is equipped with sensors able to perform the stated functions, and walks positively making use of a map, as will be explained in Section 10.

9.3. Communications between Levels B and C

Signals should be correctly communicated between Level B (especially B_2, B_3 and B_4) and Level C in both normal and emergent motions. It is found effective to construct a hand-shake type system using flags accessible from both Levels B and C. This section explains the communication system. The flags are three kinds as follows:

Flag 1: F_1: It is set when Level C calls Level B for gait operation, and is reset at completing the operation at Level B.

Flag 2: F_2: It is set when Level B notifies Level C that the gait operation is over, and is reset when Level C has received the parameters.

Flag 3: F_3: It is set when Level C calls Level B to supply calculated gait parameters, and is reset when Level C has received the parameters.

The communications system is classified into normal and emergent motions, and is presented below.

In the normal motion, the set of F_2 is confirmed first. If it does F_3 is set and the calculated gait parameters are sent to Level C. As soon as Level C receives them all, the robot starts walking. At the same time, F_1 is set to execute the new step calculation. Upon completing the calculation, F_1 and F_2 are reset in turn to wait for the next step-switch. The same process is repeated in the following step.

In the emergent motion, the starting point is at a random time during a step. As soon as the system enters the emergent mode, the torso stops moving and emergent motion is executed to match the situation. If the motion results in setting F_1, the gait operation is executed. (In the hit-evading motion, F_1 is set simultaneously with the initiation of emergent motion). F_1 and F_3 should be set at the same time. Upon completing the gait calculation, F_2 is set. As F_3 is set beforehand, the landing-position-reviewing result is passed to Level C at the moment of completing the gait calculation and the walk is resumed. Subsequently, the walk restores normal motion. Communication between Levels B and C described above enables smooth hierarchy control.

10. EXPERIMENTAL WALK

The authors designed and assembled the quadruped walking machine TITAN III as shown in Figs 17 and 18. It demonstrated the effectiveness of the control system introduced in this study. The details are presented in the following sections.

10.1. Hardware

TITAN III weighs 80 kg, has four legs each 1.2 m long, and is driven by linear actuators of 12 degrees of freedom. The linear actuators consists of DC motors of 30 W (x-, z-axes) and 20 W (y-axis), ball screws and a linear roller guide. The servo system is a software servo which detects displacement by a potentiometer and controls speed in armature-voltage control type. The foot-tip sensors are whisker sensors, using eight shape-memory-alloy wires having super elasticity. The mechanisms are not discussed here in details as they have been discussed before in reference [15]. A visual sensor is not mounted on this robot.

10.2. Construction of the control system

The control system of TITAN III is the 16-bit personal computer PC-9801 (NEC). The signals are the potentiometer input (12ch A/D), the joystick command input (2ch A/D), the accelometer-based posture-angle-sensor input (2ch A/D), the tactile-sensor input (20 bit PIO) and the command input to the 12-axis servo actuator. The tactile sensors perform the functions stated in Section 9.2. The ROM mounted at each foot-tip codes the 12-bit contact signals to the contact modes in 5-bit signals and transmits them to the central control system.

The language is the optimized C (CI-C86) on the MS-DOS. The whole control system is stated in about 70 kbyte. The operation time in a single sampling interval at Level C of this study is approximately 11 ms. The timer interruption interval is set to be 20 ms. Input/output operation of Level C is executed at the beginning of sampling. The remaining time (9 ms) is allocated to the operation of Level B. The hierarchy control system is thus constructed.

10.3. Implementation of control program

As TITAN III is not yet equipped with a visual sensor, the control programs proposed in the preceding sections are implemented in a partly modified state. The major modifications are detailed below.

The control system of Level B has a map domain which corresponds to the frontal area divided into 100×100 of 50×50 mm cells. At present, the map does not include height information. It contains information about landing-prohibiting-domain only. The information is used solely for evading motion of the foot from the landing-prohibiting-domain such as the edge of steps.

As the map does not include height information, the positions and heights of the two front legs known at the step-switching point N_k are used for determining the z

gait of the center of gravity at the step S_{k+1}. Predictive walk is possible because the two front legs are positioned ahead of the center of gravity under the normal situation. As the heights of J_u cannot be foreseen from the map, they are regarded in this study as being equal to P_u and set to be $g_z=0$, $z_{rtn}=0$.

The whisker sensor, is, at present, a contact sensor which cannot get distant information, so that the processing stated in Section 9.2(1)(c) is accomplished by switching it ON/OFF. This is shown in Fig. 19 as the foot-tip trajectory. Although it takes time for searching, it allows TITAN III to trace any extruding irregularities. Except those specifically presented here, the control programs of TITAN III employ the methodology discussed in this paper.

10.4. Walking experiment

TITAN III was first tested in a straight walk to demonstrate the effectiveness of the control system at Levels B and C proposed in this paper. The walking speed was calculated as in Fig. 16, based on the control method introduced at Section 7.1. The walking experiment proved the relation held within a feasible speed range. Then, TITAN III walked up and down stairs, as shown in Figs 17 and 18. The foot-tip trajectories in Fig. 17 demonstrated that a nearly rectangular locus was formed by the foot-tip as expected. Emergent motion which searched obstacles was actually generated as prescribed by the theory and obstacle-evading motions were implemented. Likewise, the trajectory of the center of gravity of the torso indicated that the motion of the center of gravity was smoothly controlled by the z-directional control proposed in this paper.

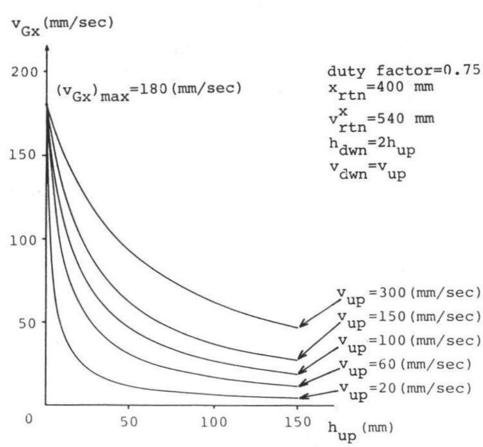

Figure 16. The effect of vertical distance, h_{up} and its velocity v_{up} of the swing leg motion to the locomotion speed of the body v_{Gx}.

Subsequently, TITAN III was further tested during a continuous walk on a flat surface under predictive control; irregularity-absorbing walk on a somewhat wavy surface, and ground-adaptive walk with the random crab-walk angle being controlled by joystick. The last experiment confirmed that changing the crab-walk angle with the joystick altered the walking direction upon completing the step and the walk converged to the new standard crab-walk gait.

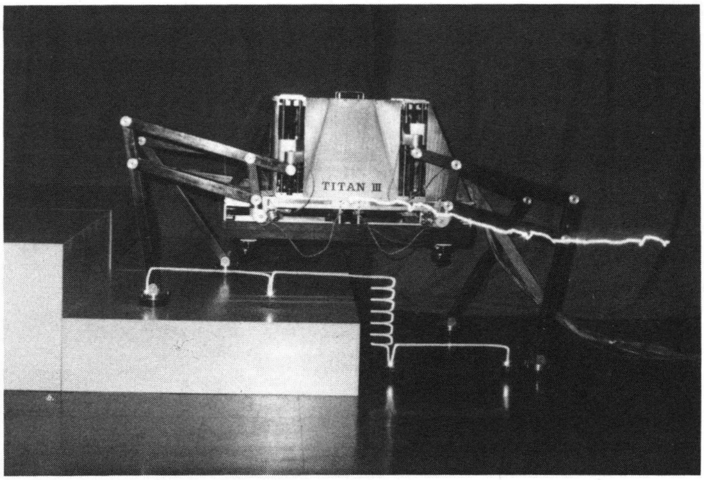

Figure 17. A walking experiment over stairs. The foot and body motion are shown by the trajectories of the lamp attached on toe and body center.

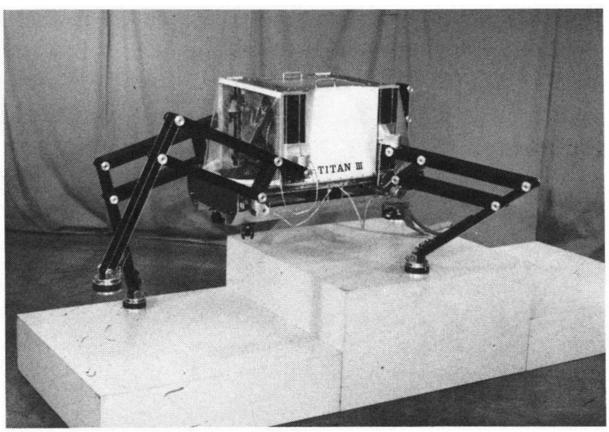

Figure 18. TITAN III walking down the stairs.

Omni-directional walk at $\pm 180°$ was possible. Figure 19 shows up/down walk on stairs. Figure 19(a–d) shows a part of the experimental walk at a crab-walking angle of 30° ($\beta = 0.8$, $v_G = 20$ mm/s). TITAN III automatically rode over a block. When the whisker sensor at the foot-tip detected one of the legs hitting the edge of the block (Fig. 19(b)), the landing position was reviewed. A better landing position was searched on the map, taking account of the edge's directional vector measured simultaneously, and the foot-steps were changed to continue the walk (Fig. 19(c)). When TITAN III came back to a flat surface, it converged to the standard crab-walk gait. The authors believe that these walk experiments prove the effectiveness of the control system introduced by this study.

11. CONCLUSIONS

The current paper has summarized the investigations so far made on the control

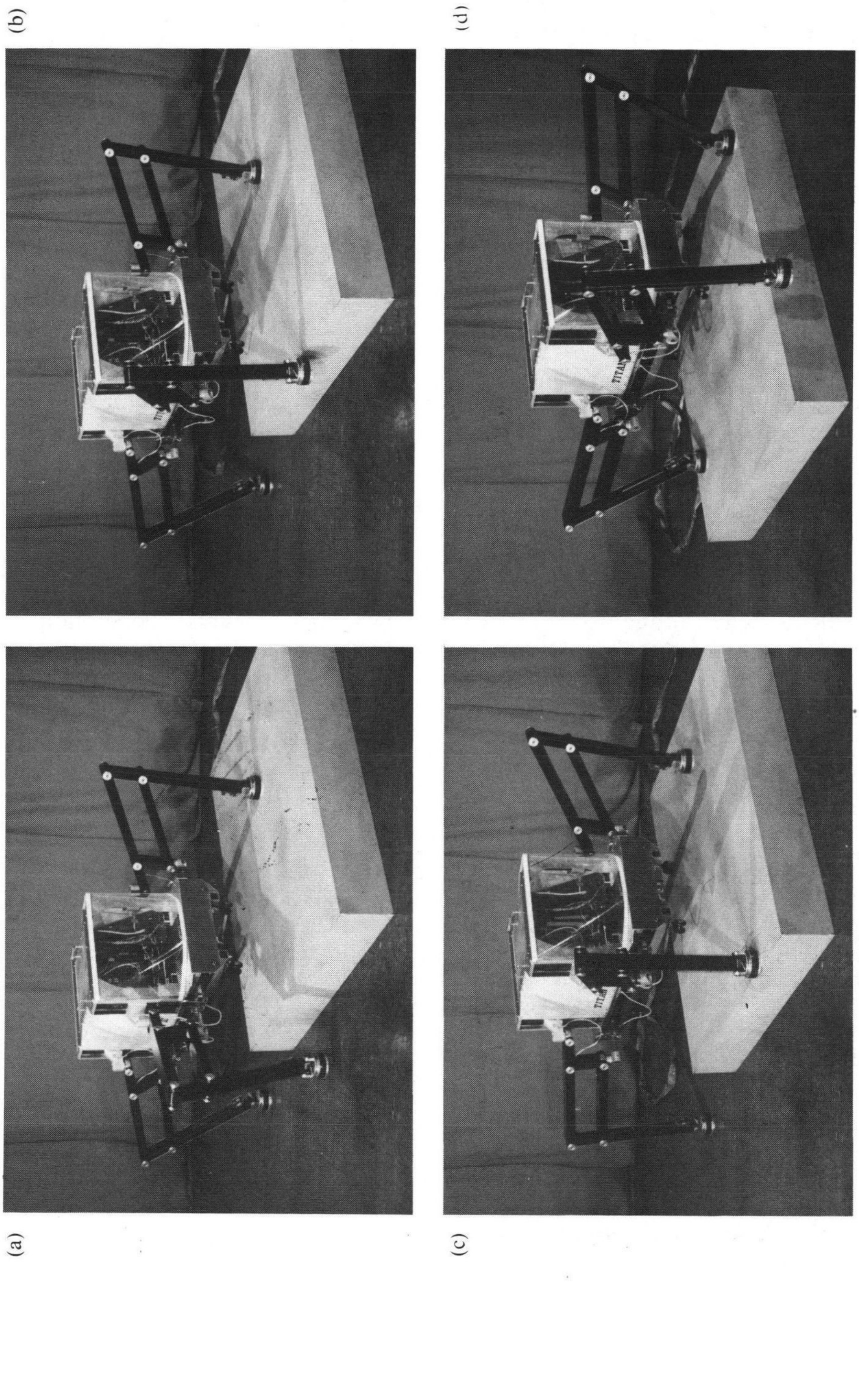

Figure 19. A sequence of the adaptive walking over irregular terrain.

system of a quadruped walking vehicle and has discussed its hierarchical architecture and the actual construction of the individual sub-systems. The effectiveness of those systems has been demonstrated by computer simulation and by the experimental walk of TITAN III. The authors believe the study has provided one of the effective footholds for future development of walking robots in under the concept of an 'artificial horse'.

More investigations are necessary on the mechanism and control system in order to improve the walking machines of robots in practical use. Problems still need to be overcome in the control system, e.g.:

(1) Construction of a perfect Level B control system by means of introducing visual sensors and better predictive control based on the additional information provided.
(2) Construction of a control system able to switch smoothly from static to dynamic walk.
(3) Construction of a control system to produce a smoother trajectory for the returning legs and the center of gravity.
(4) Integration of the circular gait proposed previously by the authors; and
(5) Construction of control system for more practical robots having reachable range of indeterminate form.

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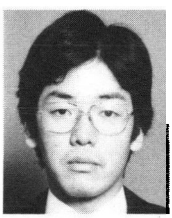
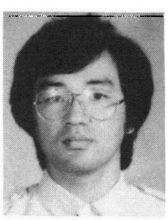
ABOUT THE AUTHORS

Shigeo Hirose was born in Tokyo, Japan in 1947. He received B.Eng. degree in Mechanical Engineering from Yokohama National University in 1971, and M.Eng. and Dr.Eng. degrees in Control Engineering from Tokyo Institute of Technology in 1973 and 1976 respectively. From 1976 to 1979 he was a Research Associate and he is at present the Associate Professor of the Department of Mechanical Engineering Science at the Tokyo Institute of Technology. His research interests are in the design of mechanisms, actuators, sensors and control systems of Robots.



Yasushi Fukuda was born in 1959. He received B.Eng. and M.Eng. degrees in Mechanical Engineering Science from Tokyo Institute of Technology in 1983 and 1985 respectively. He is currently working for Toshiba Co. Ltd., being engaged in robot development projects.



Hidekazu Kikuchi was born in 1959. He received B.Eng. and M.Eng. degrees in Mechanical Engineering Science from Tokyo Institute of Technology in 1982 and 1984 respectively. He is at present working at Asahi Chemical Industry Co., Ltd.