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Legged Locomotion Machine Based on the Consideration of Degrees of Freedom

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Summary: Minimum walking functions are defined for legged locomotion machines capable of proceeding on rough terrain. The necessary degrees of freedom are considered by using a four-legged machine which offers the minimum number of legs capable of keeping static stability and it is determined that only six are sufficient to realize the minimum functions. Although reduction of the number of active degrees of freedom generally leads to walking inflexibility, it also causes some desirable features, i.e. the simplicity of co-operational control of legs and the realization of fast locomotion, etc. From this point of view, the six-legged locomotion machine in this study is based on the idea of reducing the number of active degrees of freedom, while keeping the minimum functions. For this purpose, the approximate straight-line link mechanism is applied to the legs. It is shown that this mechanism is effective for the legs from the point of energy and in reducing the number of active degrees of freedom. This mechanism also has the possibility to realize the six-legged machine for rough terrain by only eight degrees of freedom. Although the flexibility is, of course, limited, the proposed machine can be controlled much easier than the conventional machines.

Legged locomotion machines and degrees of freedom

Table 1 shows the number of active degrees of freedom in typical legged machines[1-9] (*no steering function) which do not require any dynamic balance control. The machines which have the greatest number of active degrees of freedom possess three actuators for each leg and therefore totally such machines[1,3-6] possess with 3k active degrees of freedom (k=number of active degrees of freedom), since wheeled vehicles and crawlers can move freely with only two active degrees of freedom.

Table 1 Number of active degrees of freedom in typical legged machines.
*No steering function

4 legs	Tokyo Institute of Technology[1]	12
	Mechanical Engineering Laboratory[2]	8*
6 legs	Ohio State University[3]	18
	Moscow State University[4]	18
	Carnegie-Mellon University[5]	18
	Odetics Inc[6]	18
	Paris University[7]	12*
	Roma University[8]	12*
8 legs	Komatsu Ltd[9]	10

Generally, reducing the number of active degrees of freedom leads to the simplified control system and the fast locomotion within the limited walking functions. From this point of view, although the degrees of freedom seem to be the fundamental study in developing of the legged machine, this problem has not yet been studied thoroughly.

In this study the minimum walking functions on rough terrain are defined in the following way. It is possible: (i) to keep static stability; (ii) to move backward and forward and to steer; (iii) to keep the body horizontal; (iv) to keep the absolute height of the body constant as far as the leg length can permit.

Function (ii) means that the machine can be steered in the desired position and direction like a car. Function (iii) keeps the sufficient static stability margin and the machine from tipping over. Function (iv) is required for energy efficiency. It is also desirable to keep the absolute height of the body constant for practical actuators without energy-storing functions to save energy.

On the other hand, although it is possible for the machine with three active degrees of freedom per leg to select the suitable gait and to select the foot position freely, we can consider that these functions are related to the flexibility of locomotion but not absolutely required for the legged machine.

Necessary conditions for active degrees of freedom

Necessary conditions of active degrees of freedom have to be considered on the basis of static stability, body position and posture of support plane formed by the feet in loaded phase. It is assumed that static stability is ensured in this study. Since it is expected that fewer legs lead to reducing the number of active degrees of freedom, a generalized four-legged machine (Figure 1) is considered, where $\vec{G}$ is the

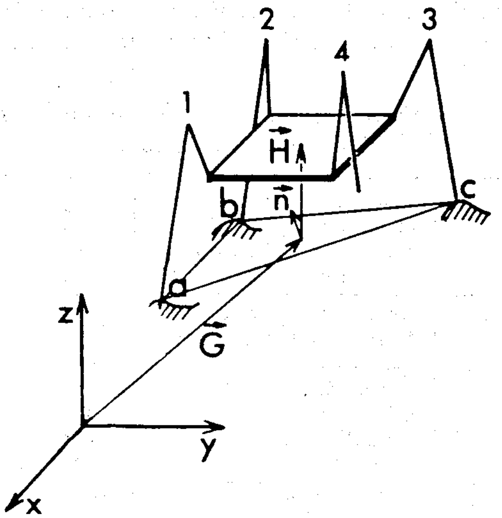


Figure 1 Generalized four-legged machine and its vector notation

vector to express the centre of gravity of the support triangle formed by the feet in loaded phase, $\vec{H}$ is the vector to express the height between the centre of gravity of the support triangle and the body and $\vec{n}$ is the unit vector and its direction is perpendicular to the support triangle. Eventually, function (ii) means that $\vec{G}$ can be determined in any position on the terrain and function (iii) means that $\vec{n}$ can be turned in any direction independent of the body posture and function (iv) means that $\vec{H}$ can be determined in any position within the legs' movable limit. Therefore, to realize functions (ii)-(iv), it is necessary that at least $\vec{G}$, $\vec{n}$, $\vec{H}$ could be determined freely. The components of $\vec{G}$, $\vec{n}$, $\vec{H}$ are expressed by

$$\vec{G} = (X_G, Y_G, Z_G) \tag{1}$$

$$\vec{n} = (\cos a, \cos \beta, \cos \gamma) \tag{2}$$

$$\vec{H} = (0, 0, h) \tag{3}$$

where a, β, γ is the angle between each axis fixed on the body and $\vec{n}$, respectively, and therefore the following relation exists:

$$\cos^2 a + \cos^2 \beta + \cos^2 \gamma = 1 \tag{4}$$

On the other hand, once the terrain is given, Z_G [in equation (1)] depends on the parameters X_G, Y_G and therefore can be written as

$$Z_G = Z_G(X_G, Y_G) \tag{5}$$

Actually, the number of independent parameters reduces in '5'. Since each independent parameter corresponds to the active degrees of freedom, five is the minimum necessary to realize functions (ii)-(iv).

Sufficient conditions for active degrees of freedom

Let us consider the four-legged model in Figure 2(a) to show the sufficiency of the necessary condition. This model is equipped with four legs and a body capable of sliding, and with a weight capable of rotating, and with one passive degree of freedom in the connecting point between its front-leg unit (or rear-leg unit) and body. The basic sequence of locomotion is shown in Figure 2(b). Since it is clear that this model has functions (i), (iii) and (iv), the problem as to whether this model can satisfy functions (i)-(iv) or not, leaves us with only having to examine the possibility of two-dimensional walking [function (ii)]. This point is demonstrated in Figure 3. The movement of $\overline{L_1 L_2}$ from the initial state to the final state can be understood as the combination with the rotation of $\overline{L_1 L_2}$ and the movement of P_1. The rotation of $\overline{L_1 L_2}$ can be accomplished easily and therefore the problem results in how point P_1 can be moved from P_1 (Xs, Ys) to P_1 (Xf, Yf). Figure 3(b and c) shows that point P_1 can be moved independently for X and Y. Therefore, theoretically it is possible for point P_1 to be moved in any position by mixing two directional movements. Since the same idea can be applied also to the rotation and movement of $\overline{L_3 L_4}$, it was proved that this model satisfies the functions (i)-(iv). Five of six active degrees of freedom in this model correspond to the number discussed in the necessary condition and the other one is required from the point of balance.

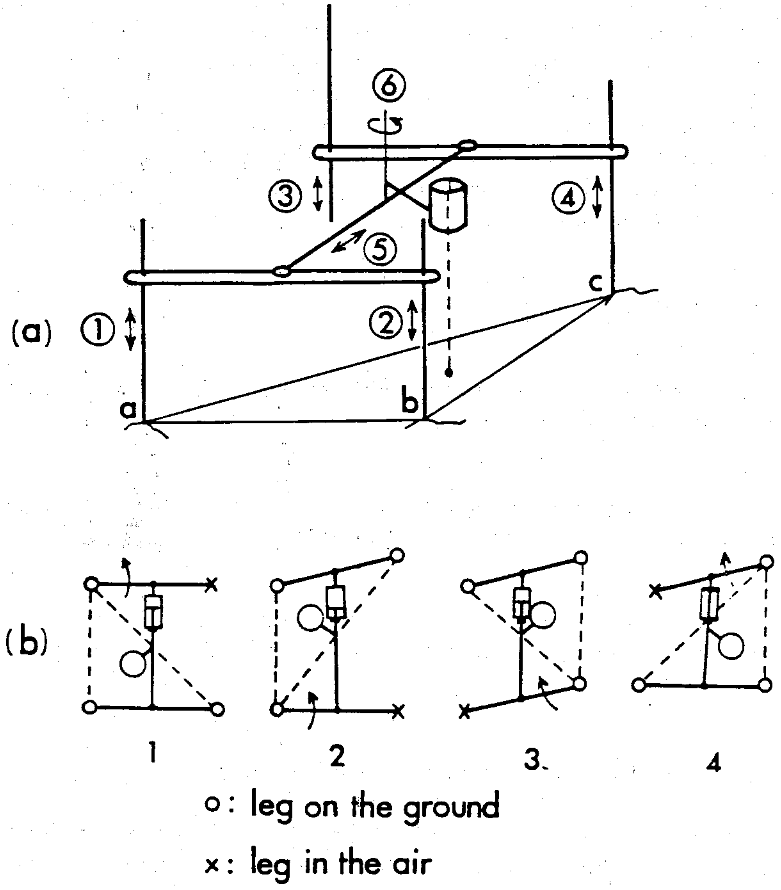
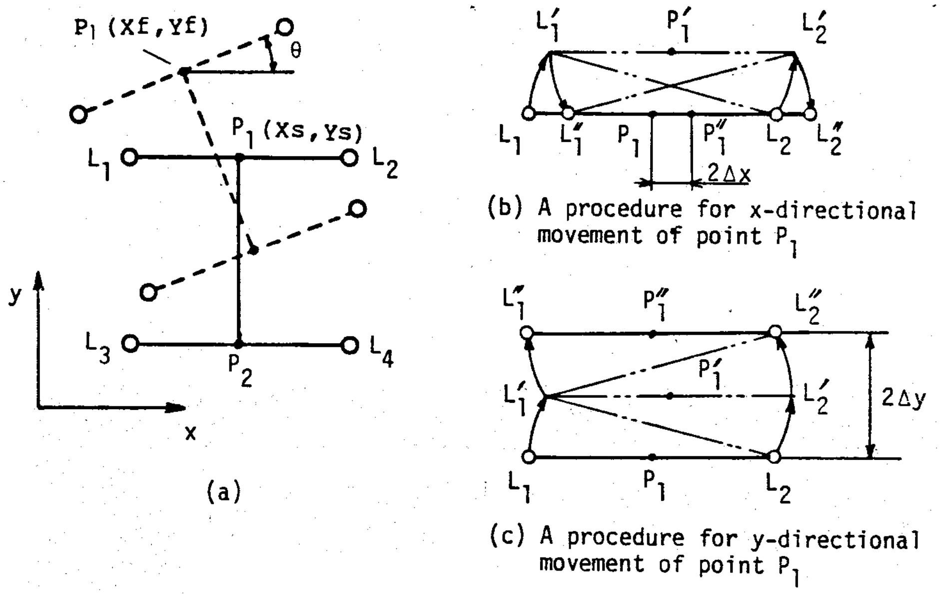


Figure 2 Four-legged machine with six active degrees of freedom and its basic sequence of locomotion

Six-legged locomotion machine based on a fixed gait

It was shown in the previous section that the four-legged machine with minimum walking functions can be realized only by six active degrees of freedom. Such a machine performs awkwardly, however, because its weight must be shifted with each step to keep its balance. Under these circumstances, we started to study the six-legged machine (MELWALK) without active balance control, and with the minimum functions and with a fewer number of active degrees of freedom. Our aim is for a more simplified machine in the same sense of controllability and a machine faster than the conventional machines[3-6]. The minimum functions can be realized by alternating a tripod gait and additional degrees of freedom. Such a gait is convenient to simplify the mechanism and to keep balance without control. An approximate straight-line link mechanism[10] is applied to the leg for this purpose. The basic link-unit construction is shown in Figure 4. Two remarkable features are



(b) A procedure for x-directional movement of point P_1

(c) A procedure for y-directional movement of point P_1

Figure 3 Two-dimensional walking of the four-legged machine

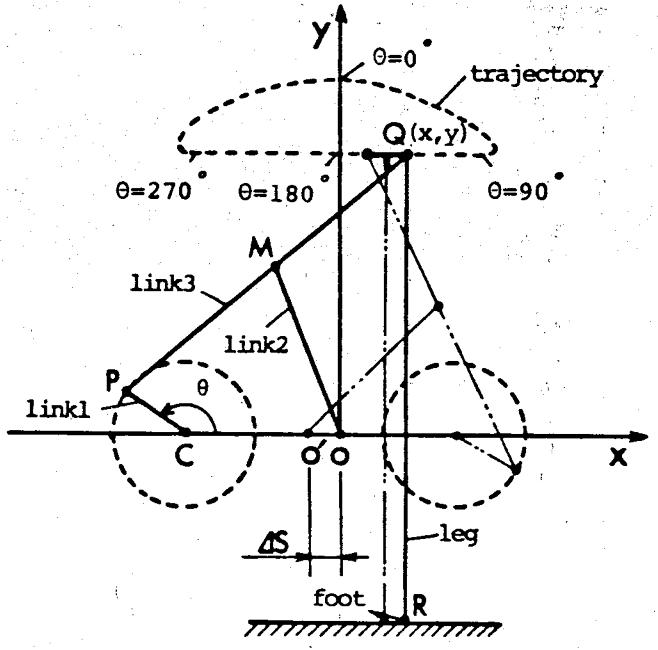


Figure 4 Approximate straight-line link mechanism and its application to leg unit

recognized in this mechanism: (1) if the approximate straight line is used as the loaded phase, the energy consumed by the reaction force of the support load is very small because the driving actuator receives extremely small feedback force caused by the reaction force; (2) since the body can be moved along the approximate horizontal surface, it also leads to reduced energy consumption because elimination of up-and-down movement of the body is essential in reducing energy consumption.

So far we have built two machines (MELWALK – mark I, II). Mark I has one active degree of freedom and therefore it can move only straight backward and forward. Mark II (Figure 5) is constructed by two bases with three legs and each base can rotate around its centre axis. Therefore mark II can move two-dimensionally on a flat plane.

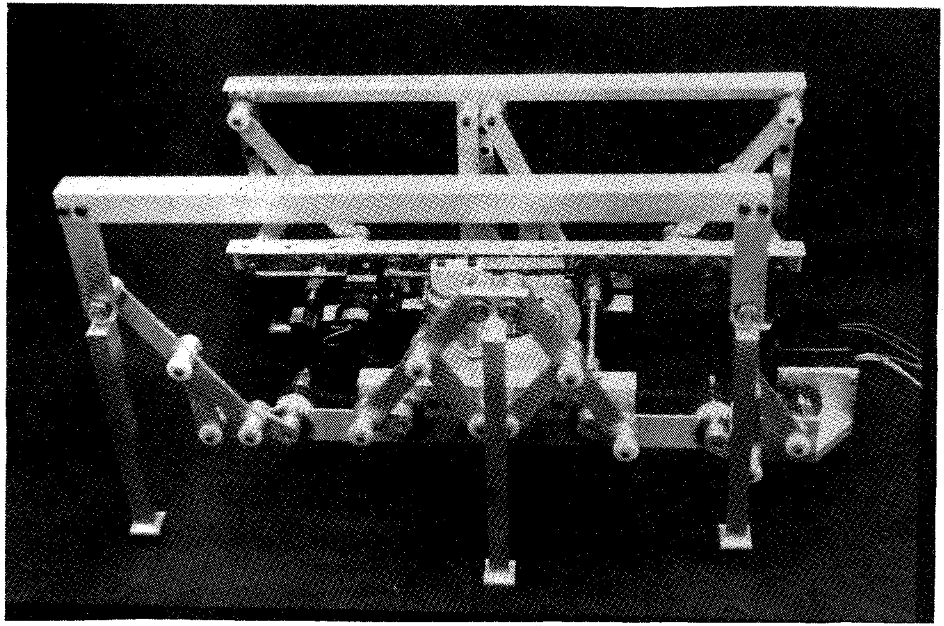


Figure 5 Six-legged machine with two active degrees of freedom (MELWALK mark II)

The specific power proposed by Gabrielle *et al.*[11] is effective to evaluate the energetic efficiency while walking.

$$\epsilon = \frac{E}{W \cdot L} \tag{6}$$

where E, W, L are energy consumption in walking, weight of the machine involving payload and distance of locomotion respectively. The specific power means the energy which the unit mass of the machine consumes during the locomotion of the unit length. The measured specific power with mark I is shown in Table 2 where $W = (M_1 + M_2)g$ and M_1, M_2 are mass of the machine and mass of payload. The specific power of the four-legged machine[1] is also shown in Table 2. Although the specific power depends on walking speed, etc., and therefore it is not a suitable way

Table 2 Specific power

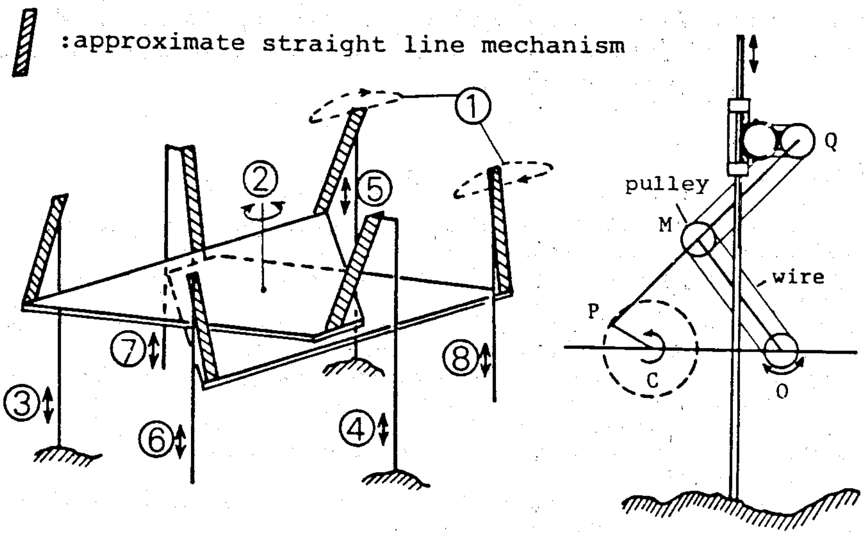
M_2 = 0 kg	0.53
M_2 = 4 kg	0.35
M_2 = 8 kg	0.30
Four-legged machine[1]	25.50

to compare both machines simply, there is no doubt that in MELWALK very little energy is required for driving the actuator. It is also recognized from the fact that mark I is capable of easily carrying payloads three times its own weight.

Application on rough terrain

The definite advantage of legged locomotion machines against wheeled vehicles is that they can proceed even on rough terrain; however mark II cannot be adapted for this terrain.

Now we are developing mark III with legs capable of lengthening or shortening as well as the other functions of mark II. As it is shown in Figure 6, by keeping the minimum functions our machine has only eight active degrees of freedom, and



(a)

(b)

Figure 6 Application of the proposed machine to rough terrain therefore 10 active degrees of freedom have been deleted from the conventional machines.[3–6] The control algorithm becomes surprisingly simple and a computer program which controls such a machine accomplishes three tasks. First, it regulates the leg length so that they adapt to the terrain just before one set of three legs changes from an unloaded phase to a loaded phase. When one of the three legs reaches its movable limit before touching the ground, the body must be shifted down. The second task is to control the actuator to propel the body along the approximate straight line or to change the body direction. This control is quite easy because each actuator can be operated independently. The third task is to avoid obstacles. When a leg in the air detects an obstacle which it cannot get over, the leg must be lifted. In the same way, when the front part of the body detects an obstacle, the three legs on the ground must lift the body synchronously.

As a result, drastic simplicity of control and fast locomotion can be expected for small sacrifices of flexibility in comparison with conventional machines.

Conclusion

The necessary and sufficient conditions on active degrees of freedom were examined under minimum walking functions defined for a legged locomotion machine capable of proceeding on rough terrain. As a result, it was revealed that at least five active degrees of freedom are required for such a machine without considering balance and six are sufficient even if the shift of the centre of gravity is considered.

To realize simplicity of control and fast locomotion, a six-legged machine based on a fixed gait was examined from the point of the specific power, degrees of freedom and controllability. It became evident that the proposed machine shows excellent values in the specific power and needs only eight active degrees of freedom even for application on rough terrain.

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