Mechanical design of walking machines

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The performance of existing actuators, such as electric motors, is very limited, be it power-weight ratio or energy efficiency. In this paper, we discuss the method to design a practical walking machine under this severe constraint with focus on two concepts, the gravitationally decoupled actuation (GDA) and the coupled drive. The GDA decouples the driving system against the gravitational field to suppress generation of negative power and improve energy efficiency. On the other hand, the coupled drive couples the driving system to distribute the output power equally among actuators and maximize the utilization of installed actuator power. First, we depict the GDA and coupled drive in detail. Then, we present actual machines, TITAN-III and VIII, quadruped walking machines designed on the basis of the GDA, and NINJA-I and II, quadruped wall walking machines designed on the basis of the coupled drive. Finally, we discuss walking machines that travel on three-dimensional terrain (3D terrain), which includes the ground, walls and ceiling. Then, we demonstrate with computer simulation that we can selectively leverage GDA and coupled drive by walking posture control.

Keywords: walking machine; mechanical design; gravitationally decoupled actuation; coupled drive

1. Introduction

Travel by walking has such interesting characteristics as shown below, which are not shared by travel with wheels or crawlers (figure 1).

— It has high travelling performance on uneven terrains.
— It travels while touching the ground discretely.
— It can stride over obstacles without touching them.
— It can travel in all directions without changing its body direction.
— It can move the body without the foot leaving the ground.
— It will give little damage to the ground. (There is no skid between the foot and the ground.)

If walking machines can fully exert these characteristics, they can replace humans in various sorts of dangerous works, such as maintenance of chemical and nuclear plants, rescue operation at the site of disasters, cargo transportation...
in mountainous areas and humanitarian land mine removal. With a suction device installed on the foot, they can perform such works as maintenance of outer walls of high-rise buildings, highway columns as well as inner walls of tunnels. Unfortunately, however, currently there are few walking machines practical enough for such works. The primary reason lies in mechanical design, especially limited performance of actuators, such as electric motors.

As for mobile machines using wheels or crawlers, essentially two actuators are enough for travel. The one is for thrust and the other is for steering. However, when it comes to walking machines, typically at least three actuators are installed on a leg in order to move the foot to the desired three-dimensional position. As walking machines need two or more of such legs, they will have far more actuators compared with mobile machines with wheels or crawlers. However, the performance of currently available actuators, such as electric motors, is very limited, be it power–weight ratio or energy efficiency. Since walking machines have many such actuators, they tend to become impractical, i.e. they can barely support their own weight while consuming enormous energy. In such difficult situations, special consideration to the leg mechanism is critical to develop a walking machine as practical as possible.

This study is centred on two concepts that are extremely useful in designing the leg mechanism of walking machines. One is the gravitationally decoupled actuation (GDA) and the other is the coupled drive. The GDA decouples the driving system against the gravitational field to suppress generation of negative power and improve energy efficiency. The coupled drive couples the driving system to distribute the output power equally among actuators to maximize the utilization of actuator power. This paper first describes the GDA and the coupled drive in detail and then presents several walking machines developed using these concepts. Since the GDA states decoupling and the coupled drive coupling of the driving system, they seem to be contradicting each other. However, they can be regarded as very similar concepts from a certain perspective. This will also be mentioned in the paper. Further, the

Figure 1. Advantage of walking machines.

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same walking machine can leverage both GDA and coupled drive selectively by 
adequately controlling the walking posture. We will explain this by illustrating a 
walking machine that travels in the three-dimensional travelling environment (the 
environment that requires travelling not only on the ground, but also on the walls 
and ceiling) called three-dimensional terrain (3D terrain).

2. Improvement of energy efficiency by decoupled drive

(a) Positive and negative power consumption

To develop a practical walking machine, the energy source such as batteries 
should be mounted on the machine. However, considering the decrease of 
travelling performance resulting from increased weight, it is not possible to equip 
the machine with so much energy. Accordingly, travelling energy efficiency is one 
of the important performance criteria of the walking machine. Energy loss is 
caused by such factors as actuator heat generation and friction. In addition, in 
the case of mechanisms driven by many actuators, such as the leg mechanism, 
there is a unique mechanism that causes large energy loss. This mechanism can 
be explained by focusing on the sign of the power generated by actuators (the 
sign of the energy generated in a unit of time).

Power has a sign, such as positive and negative power, and an actuator can 
generate both positive and negative power. Here, ‘an actuator generates negative 
power’ means that ‘power is supplied from the output side of an actuator’ or ‘an 
actuator is used for braking’. When a mechanism is driven by only one actuator, 
the power generated by the actuator is the power the mechanism outputs to the outside, 
and the signs of the power are naturally the same. However, when a mechanism is 
driven by multiple actuators, the sign of the power the mechanism outputs to the 
outside and the sign of the power each actuator generates are not always the same.

Take lifting of a weight by the mechanism shown in figure 2 as an example. 
Here, the direction of force $F$ and the direction of velocity $V$, which are necessary 
to lift the weight, are the same, so the sign of the power the mechanism outputs to 
the outside $P_{out}(= F \cdot V)$ is positive. First, in the posture shown in figure 2a, the
direction of torque, $\tau_1$ and $\tau_2$, and the direction of angular velocity, $\omega_1$ and $\omega_2$, generated by the actuators are the same, so the signs of the power $P_1$ and $P_2$ are both positive ($P_1 = \tau_1 \omega_1 > 0$, $P_2 = \tau_2 \omega_2 > 0$). On the other hand, in the posture shown in figure 2b, the direction of $\tau_2$ and $\omega_2$ generated by actuator 2 are the same and $P_2 > 0$, but the direction of $\tau_1$ and $\omega_1$ generated by actuator 1 are opposite to each other and $P_1 < 0$.

When ignoring friction and other factors, power $P_1 + P_2$ input into the mechanism and the power $P_{\text{out}}$ the mechanism outputs to the outside are equal,

$$P_1 + P_2 = P_{\text{out}}. \tag{2.1}$$

Accordingly, in the posture shown in figure 2b, $P_2$ is presented by the following equation ($P_1 < 0$):

$$P_2 = P_{\text{out}} + (-P_1) = P_{\text{out}} + |P_1|. \tag{2.2}$$

As shown in this equation, actuator 2 supplies all of $P_{\text{out}}$, the power the mechanism outputs to the outside, as well as power $|P_1|$ to actuator 1. Further, we can assume that the power supplied to actuator 1, namely, the negative power generated by actuator 1, is radiated away as heat (it is difficult to install a power regenerative system on a walking machine that must be lightweight). Accordingly, in the posture shown in figure 2b, at least $P_{\text{out}} + |P_1|$ is necessary to generate $P_{\text{out}}$.

As shown in this example, the condition where one actuator generates positive power and another actuator generates negative power is obviously unreasonable. It is also a major reason of energy loss, so such a condition be avoided as much as possible.

(b) Gravitationally decoupled actuation

Suppose a walking machine travels on a flat ground at a constant speed without moving the centre of gravity vertically. The weight of the leg is supposed to be sufficiently light compared with the body. In this case, the direction of travel and the direction of the force that supports its own weight are orthogonal, so the travel requires no power theoretically. Thus, the total of $P_i$, the power generated by actuator $i$, is always zero,

$$\sum P_i = 0. \tag{2.3}$$

Therefore, unless $P_i = 0$ for all actuators $i$, it cannot be avoided that one actuator generates positive power while another actuator generates negative power.

Here, we consider two types of walking machines shown in figure 3. As for the walking machine shown in figure 3a, each joint must generate both torque and angular velocity except when the shank is vertical to the ground. Therefore, the power generated by each actuator is not zero, and one actuator generates positive power and the other generates equivalent negative power. On the other hand, as for the walking machine shown in figure 3b, the transatory actuator b1 needs to generate only velocity and no force, and b2 only force and no velocity theoretically. Therefore, the power generated by both joints is always zero. Accordingly, it is assumed that the walking machine in figure 3b has higher travelling energy efficiency than the walking machine in figure 3a. In reality, the acceleration cannot be zero, the weight of the leg cannot be zero and there exists friction. Therefore, the
actuator $b_1$ also generates force and the actuator $b_2$ also generates velocity. But in relatively slow-speed travelling without lifting up the leg too high, the intensity of the power due to these effects is assumed to be quite small.

The GDA aims to make the power generated by all actuators to zero and increase energy efficiency when performing a motion which theoretically requires no power. This can be achieved by so designing the mechanism and control such that the actuator which generates force (torque) does not generate velocity (angular velocity), and the actuator which generates velocity does not generate force, as in the machine shown in figure 3b.

(c) **Walking machines based on GDA**

Figure 4 shows an image of the quadruped walking machine TITAN-III and the outline of the leg mechanism called ‘PANTOMEC (three-dimensional pantographic mechanism)’ (Hirose et al. 1985). The conventional pantograph mechanism can move in the plane only. On the other hand, the PANTOMEC can move in three-dimensional space while retaining the functionality of the pantograph mechanism. In figure 4b, point $R$ is driven in the vertical direction and point $Q$ is driven in the horizontal plane. When point $R$ is fixed and point $Q$ is driven in the horizontal plane, point $P$ (toe) also moves in the horizontal plane. On the contrary, when point $Q$ is fixed and point $R$ is driven in the vertical direction, point $P$ also moves in the vertical direction. Further, the motion of point $P$ is magnification of motion of point $Q$ or $R$.
As shown in this, while the PANTOMEC, TITAN-III’s leg mechanism, seems to be a simple mechanism composed of rotating joints, it is actually equivalent to a three-dimensional expansion of the mechanism shown in figure 3b. Owing to this mechanism, TITAN-III attains the GDA and shows high travelling performance.

Figure 5 shows an image of the quadruped walking machine TITAN-VIII (Hirose & Arikawa 1999, 2001). The leg mechanism of TITAN-VIII is a standard mechanism composed of rotating joints. This leg mechanism is driven by three actuators. TITAN-VIII attains the GDA not by particularizing the leg mechanism to GDA, but by optimizing the walking posture. Its standard walking posture is the one with the legs extended sideways to the direction of travel as shown in figure 5. This posture is to attain the GDA (naturally it can walk in other postures than the standard walking posture). In this posture, joint 1 needs to generate angular velocity to swing the leg back and forth, but it is less necessary to generate torque. Joint 2 needs to generate torque to support its own weight, but it is less necessary to generate angular velocity. Further, since the shank is always kept almost vertical to the ground, it is less necessary for joint 3 to generate torque or angular velocity. In other words, this walking posture attains the condition that the power generated by each joint is almost zero, so the GDA condition is achieved. Here, the inertia of TITAN-VIII’s leg is quite small, because all actuators (DC motors) are mounted near the body and the joints are driven through the wires. Therefore, the torque to swing and lift up the leg is quite small. As shown here, the GDA can be achieved not only by arrangement of the mechanism, but also by posture control.

3. Improvement of output power by coupled drive

(a) Actuator power–weight ratio and machine performance

Many actuators are required to provide the capability of diverse motions to a machine. However, as we mentioned before, the power–weight ratio of currently available actuators is severely limited, so if many actuators are installed without
much consideration, it will result in excessive weight increase. As a result, the machine will suffer the dilemma that while it is equipped with many actuators to realize diverse motions, its own weight seriously impairs its motion performance. When the machine is fixed on the ground, as in the case of industrial manipulators, this dilemma can be solved to an extent by placing actuators at the base. However, when it comes to mobile machines that need to support themselves and travel, such a measure is useless. Among various mobile machines, this dilemma is of special concern for walking machines that need a particularly large number of actuators.

(b) Coupled drive

The design method to deal with this dilemma is the coupled drive we describe here. First, we introduce the basic concept of the coupled drive, taking two types of bicycles shown in figure 6 as an example. Figure 6a is a regular bicycle and figure 6b is a sport bicycle. The actuator for human is muscle. Riding a regular bicycle needs only leg muscles. On the other hand, riding a sport bicycle needs not only leg muscles, but also muscles of the entire body. Therefore, even when the rider is the same, a sport bicycle can generate more speed than a regular bicycle. In other words, the person on a sport bicycle uses the equipped actuators (muscles) more effectively.

Machines can also attain a greater output by maximizing the utilization of installed actuators. Therefore, we define the actuation index $\eta_p$ with the following equation as a quantitative index to indicate the utilization of installed actuators:

$$\eta_p \equiv \frac{\text{possible output power}}{\text{sum of installed actuators power}}.$$  \hfill (3.1)

The maximum value of $\eta_p$ is 1, and $\eta_p=1$ means that all actuators exert the maximum power to perform the intended motion. Further, the more equally the output power is distributed among installed actuators according to their maximum output power, the larger the actuation index $\eta_p$ becomes. The basics of the coupled drive is to optimize the mechanism and control so as to maintain $\eta_p$ as high as possible, and to minimize the impact from weight increase resulting from installation of many actuators (Hirose & Sato 1989).
Then, we take the wall walking machine as an example to explain the coupled drive more specifically. First, we discuss wall climbing motion of two types of wall walking machines shown in figure 7. The leg mechanism of both the machines is driven by two translatory actuators. For the sake of simplification, the maximum output power of each actuator is assumed to be the same. The wall walking machine in figure 7\textsuperscript{a} uses only actuator c\textsubscript{1} for wall climbing. Accordingly, it uses only half of the total power of installed actuators. On the other hand, the wall walking machine in figure 7\textsuperscript{b} uses both the actuators, d\textsubscript{1} and d\textsubscript{2}, for wall climbing. In other words, even though the total power of installed actuators is the same for these two machines, the wall walking machine in figure 7\textsuperscript{b} can use twice as much power as that in figure 7\textsuperscript{a} for wall climbing, and the wall walking machine in figure 7\textsuperscript{b} is more desirable from the viewpoint of coupled drive.

Then, we discuss wall climbing motion of the wall walking machine shown in figure 8. The leg of this machine is also driven by two translatory actuators. The maximum power of each actuator is also assumed to be the same. When looking at this machine, it seems natural that it climbs a wall in the posture shown in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Wall walking machine and coupled drive 1 (side view).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Wall walking machine and coupled drive 2 (top view).}
\end{figure}
However, the translatory actuator that drives the machine in the horizontal direction does not contribute to wall climbing in this posture. On the other hand, when it takes the posture shown in figure 8a to climb a wall, it can use the power of all actuators for wall climbing. In other words, from the viewpoint of the coupled drive, the posture shown in figure 8b is more desirable in wall climbing than the posture shown in figure 8a.

(c) Walking machines based on coupled drive

Figure 9 shows an image of the quadruped wall walking machine NINJA-I and its leg mechanism (Hirose et al. 1991). Each leg is equipped with a suction cup and the machine uses these cups to climb the wall. The foot is so constrained by the central shaft such that it will move in polar coordinates (a retractable spline shaft is attached to the body via a universal joint), which is driven by three translatory actuators. The translatory actuators are composed of a DC motor and a ball screw. The leg mechanism of NINJA-I is a three-dimensional expansion of the leg mechanism shown in figure 7b. All translatory actuators are placed almost in parallel, so it can fully use the power of installed actuators for wall climbing, which require the largest power among all the motions. Figure 10 shows an image of NINJA-II (Nagakubo & Hirose 1994), an improved model of NINJA-I. NINJA-II’s leg mechanism is also driven by three translatory actuators placed almost in parallel, but this motion is magnified by the link mechanism, which enables a large range of movement. NINJA is capable of not only travelling on a flat wall, but also moving from ground to wall and from wall to ceiling as well as transferring between walls at the corner (e.g. from the north wall to the east wall) by taking advantage of the unique characteristics of the walking machine.
4. Decoupled and coupled drive

(a) Interpretation of GDA from coupled drive

Up to this point, we have described the GDA and the coupled drive. The GDA states decoupling and the coupled drive coupling of the driving system, and therefore they may seem to be contradicting concepts. However, these concepts can be regarded as highly compatible from a certain perspective and the GDA can be interpreted from the perspective of coupled drive.

In the GDA, when performing a motion that requires no power, the power generated by each actuator should be zero (see §2b). On the other hand, in the case of coupled drive, the output power should be equally distributed among installed actuators (see §3b). Here, we suppose a condition not desirable in the GDA, namely, an actuator generates negative power and another actuator generates positive power though the required power is zero. As we explained before, the actuators that generate negative power receive power from the actuators that generate positive power. The power load of the actuator that generates positive power is heavier than that of the actuator that generates negative power. This situation can be assumed that output power is distributed only to the actuators that generate positive power. In contrast, when the GDA is attained, or each actuator generates no power, we can assume that the output power (=0) is equally distributed among all actuators. This is precisely the condition desired by the coupled drive.
Walking machines for three-dimensional terrain

The travelling environment which includes not only the ground but also walls and the ceiling is called the 3D terrain. Recently, the need for mobile machines that can travel on the 3D terrain is intensifying in various fields, such as maintenance of outer walls of high-rise buildings and highway columns as well as inner walls of tunnels. Travelling on the 3D terrain requires far more diverse motions compared with travelling in the ordinary travelling environment, for example, moving from ground to wall and from wall to ceiling. Therefore, the walking machine is assumed to be most suitable for travel on the 3D terrain.

Here, we focus on two principal motions for travelling on the 3D terrain, namely ground walk (travelling on the horizontal ground) and wall climbing (climbing a vertical wall). As mentioned in §2b, the concept of GDA is useful for design and control of walking machines for ground walk. Further, as mentioned in §3b, the concept of coupled drive is useful for design and control of walking machines for wall climbing. Walking machines that travel on the 3D terrain need to perform both ground walk and wall climbing, and it is desirable that they can use both GDA and coupled drive to ensure high travelling performance. However, the leg mechanism optimized for ground walk, as the one shown in figure 3b, is difficult to use the coupled drive on wall climbing, and the leg mechanism optimized for wall climbing, as the one shown in figure 7b, is difficult to use the GDA on ground walk. Accordingly, we aim to adjust the walking posture in accordance with the travelling environment so as to take advantage of GDA and coupled drive, instead of optimizing the leg mechanism to the GDA or coupled drive (Arikawa & Hirose 1995).

We assume a leg mechanism driven by three actuators, as shown in figure 11, for the walking machine that travels on the 3D terrain. This leg mechanism is not optimized for the GDA or coupled drive, but a standard mechanism. Further, we assume that the direction of force generated by the foot touching the ground or wall is $-Z$ on ground walk and $-X$ on wall climbing, and the direction of velocity is $-X$ on both ground walk and wall climbing. Figure 12 shows the power generated by actuators when a foot is on the plane represented by $Z=-0.1\,\text{m}$. The segments that stretch from the point of the foot to the above,
lower right and lower left correspond to the power generated by actuators 1, 2 and 3, respectively (see figure 11). The solid line indicates positive power and the broken line indicates negative power, and the length of the segment indicates the intensity of the power.

First, we examine ground walk. Negative power is generated in an extended area within the movable range, but when the foot is in areas GA and GB, it is found that there is little negative power and the power generated by all actuators is zero. (When the foot is in area GA, the shank is vertical to the ground, and when the foot is in area GB, the leg is orthogonal to the direction of travel.) In other words, when the foot is in areas GA and GB, the GDA condition is achieved. Judging from the shape of these areas, if the machine walks in the walking posture as shown in figure 13 ground walk using the hatched area in figure 12a, it can walk mostly maintaining the GDA condition.

Then, we examine wall climbing. It is found that negative power is not generated except for the area near the origin, but the power generated by actuators significantly fluctuates in the movable range. For example, when the foot is in area CA, most of the power is generated by actuators 2 and 3, and when the foot is in area CC, most of the power is generated by actuator 1. As mentioned in §3b, the more equally the output power is distributed among actuators according to their maximum output power, the larger the actuation index $\eta_p$ and the effect of coupled drive become. Accordingly, for example, when the maximum output power of each installed actuator is the same, if the machine walks in the walking posture as shown in figure 13 wall climbing using area CB in figure 12b, it can attain the coupled drive.

As shown above, when walking on the 3D terrain, by selecting the most appropriate walking posture in accordance with the travel environment, the effect of GDA and coupled drive can be realized.

Figure 12. The power each actuator generates in ground walk and wall climbing.
5. Conclusions

This study discusses the method useful to design a walking machine with high travelling performance, with focus on two concepts, GDA and coupled drive. When performing a motion that requires no power, the GDA decouples the driving system to make the power generated by actuators to zero and improve travelling energy efficiency. The coupled drive couples the driving system to distribute the output power equally among actuators according to their maximum output power and maximize the utilization of installed actuator power. Currently available actuators have limited power–weight ratio and energy efficiency, which poses a severe restriction on the design of walking machines. However, even under these circumstances, application of GDA and coupled drive will enable practical walking machines.

References


