Locomotive Characteristic Analysis of Terrestrial Vertebrates for the Modeling of Four-Legged Walking Machine

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ABSTRACT

The coordinated mechanism of terrestrial vertebrates enables them to maneuver over all of the terrain conditions since they have a distinct ability to adapt to varying conditions. Their locomotions remain infinitely more advanced and elegant than that of present-day existing mechanical walking robots. However, the principles of existing walking robots are based more on technical rather than on biological concepts, yielding unstable locomotion with low speed. In order to apply these advanced biological phenomena to the mechanical design of 4-legged walking robot, modeling methods are introduced and mathematical equations are also introduced.

Key Words : Stroke, Pitch distance, Duty factor, Transfer phase, Support phase, Stability margin

1. Introduction

Almost all of the vehicles have made use of wheels or tracks. This is in contrast to the locomotion of human and animals in which the function is done by the acquired individual link mechanism. Vehicle or rail systems are clearly superior to animals for efficient, long-distance transportation, but these advantages apply only for the movement on the prepared surfaces(1). That is the synergistic combination of wheels with rails or roads that produces an effective system. In fact, for off-road locomotion, the situation is quite the reverse. Whereas off-road vehicle speeds are typically limited to a few miles per hour, and power requirements are in the range of 10 HP per ton, large mammals are able to traverse the same terrain with an order of magnitude more speed and at a considerably reduced energy cost(2). These facts have motivated much of the research to date on the possible application of legged locomotion principles to the design of legged walking machine(3) for use either as off-road vehicles or as rough-terrain robots.

Other advantage of legged locomotion is to be found in the superior mobility exhibited by animals and man in comparison to automotive vehicles. Interaction of wheels or tracks with terrain differs from that of legs, on the soft or slippery ground. Wheels or tracks

2. Gait of Terrestrial Vertebrates

From the biological concept, Uspenskii(4) defined gait as follows: "Gait is a complex, strictly coordinated rhythmic movement of the entire body of the animal treated as an integral complex of reflex acts that occur in accordance with the conditions of the environment and which are capable of producing progressive movements of different types inherent in each animal species." Therefore, for a certain motion of an animal or a walking machine, a gait can be defined. Since the number of legs, the leg geometry, the mobility performance, and the control of the walking machine are very much related to the adopted gait, a complete understanding of gait is very important in designing a walking machine.

In 1899, Muybridge(5) worked on developing the concept of gaits in animals and distinguished new forms of locomotion after proper characterization. His main contribution is the compilation of photo albums of moving persons, horses, different domestic animals, and a few wild animals. It was possible for him to show locomotory cycle through a series of successive snaps indicating the relative portion of legs and the animal itself with regard to the substratum at various moments in the cycle. Although his analysis was not complete, his photographs provide invaluable material for further research.

Howell[6] developed the concepts of gait. He modernized the diagram method of gait representation suggested by Muybridge. Taking each gait in a sequence, he divided the support plan into eight stages. But he depicted the support plan of stage in a different manner using horizontal lines with points near the end to indicate supporting legs. In this connection, the points lying on the top and on the bottom near the right end of the line correspond to the left and right forelegs; points lying near the lower end correspond to the hind legs. Such a system of recording provides a better graphical interpretation of the dynamics of the locomotory cycle when compared with the original records of Muybridge.

Progressive movement or locomotion in animals takes place in different ways. Some animals use a wide variety of gaits, ranging from fast to slow, which can be more economical and effective in a particular situation, even though requiring large expenditures of energy.

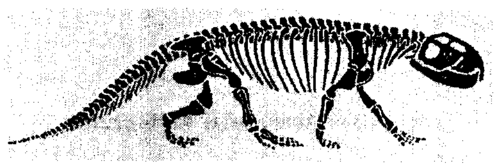

Fig. 1 Model of Terrestrial Vertebrate for the 4-Legged Walking Machine Design.

Other animals have a limited choice of locomotory types. There is no generally accepted classification of gaits which could be applied to all animals and there is no clear understanding of the biological phenomena reflected in these gaits. And until recently, zoologists did not realize the importance of different modes of locomotion in mammals characterizing the biomechanical aspect of animal locomotion.

2.1 Gait Classification

The first photographic technique by Muybridge made it possible to analyze the gaits of all kinds of animals in unprecedented detail. Later, Sukhanov[7] classified the gaits of terrestrial vertebrates as follows:

1. Walk
    - Very Slow Walk
    - Normal Walk
    - Fast Walk
2. Trot-Like Walk
    - Slow Trot-Like Walk
    - Fast Trot-Like Walk
3. Trot
4. Amble-Like Walk
    - Very Amble-Like Walk
    - Fast Amble-Like Walk
5. Amble
    - Slow Amble
    - Fast Amble

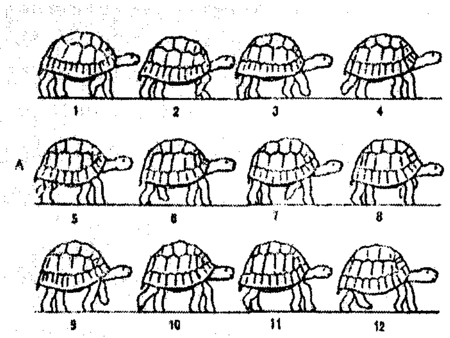

Fig. 2 Side View and Gait Diagram of Very Slow Walk in Turtle by Sukhanov[7]

The walk is the four-paced gait with equal intervals between the movements of all four legs. Supportive and propulsive efforts are continuous and of the same type, which gives a firmness to the walk and enough effectiveness in the entire duration of the cycle.

Very Slow Walk is characterized by a rotation of tri- and quadrupedal stages by the formula: 4-3-4-3-4-3-4-3, 4 legs in ground contact, then 3 legs in ground contact, etc., as shown in Fig. 2. Each rear leg leaves the ground earlier than the front one of the same side. This prevents the increases of step length during the locomotion of this gait. An increase of movement results in an absolute and relative decrease in the duration of quadrupedal stages, which finally drop out and the cycle becomes 3-3-3-3.

Normal Walk is the main gait for the majority of mammals during slow movement. This walk is characterized by a rotation of bi- and tripodal stages by the formular : 2-3-2-3-2-3-2-3, as shown in Fig. 3., where secondary quadrupedal stages of a very slow walk are replaced by the stages of diagonal support, but the primary by the lateral support. Unlike the very slow walk, each hind leg does not land earlier than the liftoff of the ipsilateral foreleg. Consequently, greatly increasing the walk and crossing into a movement with an overlapping footstep is possible.

Fast Walk is characterized by a rotation of biopedal stages, alternately of diagonal and lateral, with a unipedal stage according to the formula : 2-1-2-1-2-1. The tripodal stages of slow walks are replaced by unipedal walks where the primary tripodal types have been replaced by one front leg support, but the secondaries are on one hind leg support. The fast walk is the main gait for several large and heavy-weight mammals during speedy locomotion, but it is rarely met in nature.

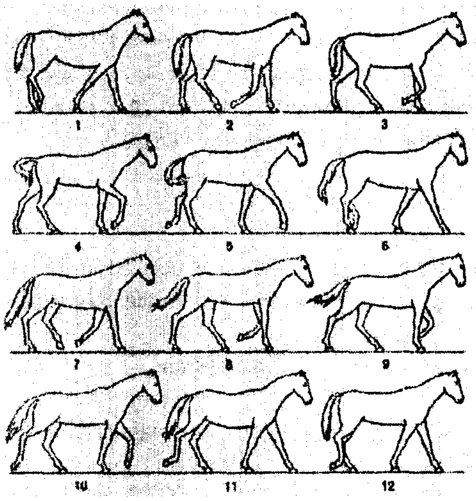

Fig. 3 Side View and Gait Diagram of Normal Walk in Horse by Sukhanov[7]

3. Mechanical Analysis

As exaplained in above Section, gait is a precise record of a series of leg and body movements which enable a legged system to move from one place to another. Gait can be described as a mathematical function which relates the legged robot geometry, including the leg workspaces and geometric relationship among these workspaces, to the performance. Gait analysis is one of the fundamental areas in the study of legged robot. It is important because it affects the geometric and control design of a legged system. Gaits have been studied quite extensively by the researchers[8][9][10].

From the leg design point of view, the goal of gait study is to check the relationships between the mechanical efficiency and the gait pattern. It would be ideal if the operator or a computer determines the gait pattern which makes the mechanical efficiency maximum for the given terrain or locomotive conditions.

The following three Lemmas give the general rules for the calculation of foot points with respect to the body coordinate system or the hip joint coordinate system, which also give the general rules for the calculation of gait stability margin.

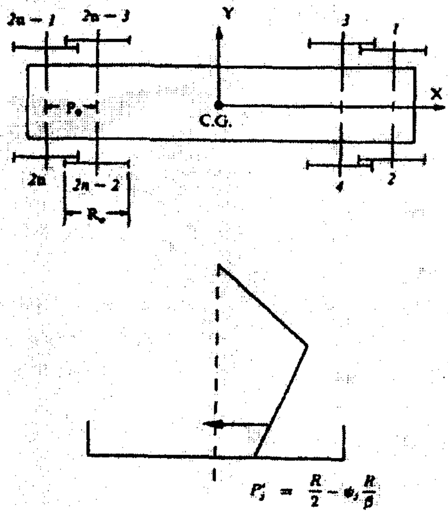

Fig. 4 (a) Coordinate of the Center of Stroke with respect to Body Coordinate. (b) Leg Position in Transfer Phase

Lemma 4-1 : The Fractional Function, $F(X)$, of a real number X is define as follows:

1. If $X>0$, $Y=$ the fractional part of X
2. If $X<0$, $Y=$ 1-the fractional part of $-X$.

According to the $F(X)$, the following rules can be established.

$$F(F(X))=F(X)$$
$$F(-X)=1-F(X)$$
$$F(N+X)=F(M+X)\text{, N and M are integer}$$
$$F(A+F(B))=F(A+B)$$

Lemma 4-2 : The position of supporting legs of a 2n-legged robot with respect to the body frame, which is attached to the body and whose origin coincides with the body center, can be calculated as follows. Referring to Fig. 4, the y-coordinate of the center of stroke of any leg-j with respect to the body center is

$$y_j = \frac{(n-j)}{2}P, \qquad j = odd\,(1,3,5,\cdots)$$

$$y_j = \frac{(n-j+1)}{2}P, \qquad j = even\,(2,4,6,\cdots)$$

Since the speed of the vehicle is R/β, the velocity of the feet on the ground is $-R/\beta$ relative to the body. The position of foot j relative to the center of stroke is

$$P_j' = \frac{R}{2} - \psi_j \frac{R}{\beta}$$

Hence, the position of foot j on the ground can be calculated as

Lemma 4-3 : For the 2n-legged periodic, regular, and symmetric gait, any support pattern has a mirror symmetric support pattern about the longitudinal body axis in one locomotion cycle. The time phase between each pair of symmetric support patterns is 1/2.

Proof: Let the leg on the left side have arbitrary phases x_{2i-1} , where $i = 1, 2, 3 \cdots n$. Due to the symmetric feature, the phase of the right leg is

$$\phi_{2i} = F(\frac{1}{2} + y_{2i-1})$$

At any time phase t_1 after leg 1 is placed, $0 \le t_1 \le \beta$, the local phases of the legs on the left and on the right are

$$\psi_{2i-1} = F(t_1 - y_{2i-1})$$

$$\psi_{2i} \ = F(t_1 - \frac{1}{2} - y_{2i-1})$$

Hence, the position of each foot, P_j relative to the center of the stroke becomes

$$P'_{2i-1} = \frac{R}{2} - F(t_1 - \frac{1}{2} - y_{2i-1})\frac{R}{\beta}$$

$$P'_{2i} \ = \frac{R}{2} - F(t_1 - y_{2i-1})\frac{R}{\beta}$$

After half-cycle of locomotion, time phase t_1' becomes $t_1 + 1/2$. Substitute t_1' into t_1 in the above equations to find the new position of each leg, p_j', relative to the center of the stroke:

After a half-cycle, the foot positions on the left become the foot positions on the right and vice versa. Thus, the support patterns of the second half-cycle are symmetric to the support patterns of the first half-cycle about the longitudinal body axis.

Lemma 4-4 : For the 2n-legged periodic, regular, and constant phase increment gait any support pattern has a

$$P'_{2i-1} = P_{2i}$$

$$P'_{2i} \ = P_{2i-1}$$

second support pattern that is mirror symmetrical with it about the lateral body axis, which goes through the center of the body and is perpendicular to the longitudinal body axis in a locomotion cycle. The fraction of a cycle period from a support pattern to its mirror image is

$$\Delta t = \beta - F\{2t-(n-1)X\}$$

where t is the time fraction of the specified support pattern after leg 1 is placed, and X is the constant phase increment.

4. Conclusion

A series of leg and body movements of terrestrial vertebrates can be expressed by mathematic equation as a function of time, which can be directly applied to the design of legged walking robots and will open the new age of walking robots.

5. Acknowledgement

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