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Design and Test of a Six-legged Walking Machine

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Abstract: This study introduced a six-legged walking machine with new leg structure, analyzed this walking machine's mechanism and tripod gait and transmission system. With modeling in PRO/E, we imported the model into ADAMS, simulation results showed the motion curve of the walking machine in three dimensional. Prototype test showed the walking machine's straight walking capacity and provided a basis for improvement. The results of test proved the design's rationality and revealed some problems need to be optimized, such as leg stuck even machine's body sink. This design showed a valuable way in walking machine's walking mechanism.

Key words: Six-legged walking machine, gait analysis, model test, prototype test

INTRODUCTION

Walking machines are a sort of robots for which use for translocation legs and the motion of them can be similar to insect or mammal moves (Graca and Zimon, 2009). The structure design of this kind of robots puts great contribution to its environmental adaptability and walking stability on complex and nasty non-structure environment where human's activities need to be replaced by machine (Wang *et al*., 2009). It has broad application prospects in many fields, such as mountain transport, satellite detection, disaster relief and rescue, mineral exploitation and military affairs. Currently, many researchers paid attention to the design of multi-legged walking machine, especially six-legged walking machine. Greiner *et al*. (1996) had developed the ALUVs (autonomous legged underwater vehicles) which has six legs. ALUVs can walk under the water and clear sea mines by self-explosion. Delcomyn and Nelson (2000) designed six-legged biomimetic robot-Biobot. Its movements are driven by pneumatic component, using unique structure to mimic muscle characteristics. Wilcox *et al*. (2007) provides a robotic vehicle called ATHLETE which uses wheels on six legs. ATHLETE is designed for rough and steep lunar terrain and each limb can perform complex tasks independently. All these walking robots have adopted serial mechanism leg structure, each leg needs 2 or more motors to drive and control the leg attitude, therefore, these robots must apply complex control system and complicated driving system. Because of the complex structure and demanding precision of control (Vitek and Blankenship, 1999; Kriz and Milliner, 2003), walking machine's reliability and stability are still unable to meet the practical requirements.

This study presents a new type of six-legged walking machine. This six-legged walking machine adopts new structure and the tripod gait, as well as six legs driven by one motor. One unique advantage of this walking machine is that the walking movement can be realized without any complex control system. A second unique advantage is that the center of gravity height jitter of this machine is negligible.

DESIGN OF THE SIX-LEGGED WALKING MACHINE

Design of leg: Leg structure is the core component of multi-legged walking machines which features determine the basic properties of multi-legged walking machine. Leg structure of this walking machine use six linkage (Fig. 1). Crank is the antriebstange, bracing swing around sleeve. When crank fixed to the shaft at one end, link 3 swings around the joint C and Joint D back and forth, preparing the institution for preliminary leg open and contractile function. When the joint B in the sleeve, joint B subject constraints from sleeve rather than turning, so joint D and joint C hold up the machine body, link 3 's swing make the body moving forward.

Crank rotating 360° around the drive shaft center completes a operation cycle. In the first 180° of crank rotation, as joint B in the sleeve, link 1 and 2 is equivalent to an overall, link 3's swing make the body moving forward. In the last 180°of crank rotation, joint B leaves

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sleeve, goes into rotating pair. Under the action of joint B, C and D and link 4, 3 lift off the ground, no longer support the body, achieve the movement. This leg structure can convert single rotary motion into leg walking exercise directly and has similar moving gesture with quadruped mammals.

Gait selection: Gait is the process that single leg put up and down according to a certain order and trajectory (Cuiping, 2007). Gait choice should based on the leg structure. Suitable gait is the basis of the walking machine to realize continuous stability walking motion. Currently, most of the six-legged walking machine using tripod gait. Triangle gait refers to three pairs of legs are divided into two groups, with alternating triangular support structure to move forward (Fig. 2a), number 1, 3, 5 legs for a group, No. 2, 4, 6 legs for the other group, thereby formed two triangular brackets. Tripod gait time plan for each leg shown in Fig. 2b, the gray portion represents contact with the ground (Danpu *et al*., 2011). When all the legs of one triangular bracket lift off the ground, the other triangular bracket's legs support the body and provide the driving force for forward movement. Two groups of legs touch the ground alternately. The machine center of gravity projection is always falls in the triangular bracket projection which has very good stability.

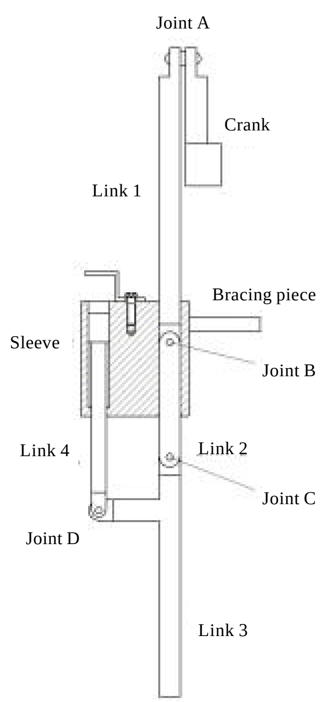

Fig. 1: Structure of leg

Design of transmission system: There are many aspects should be considered in transmission system design, including leg arrangement, motor position and transmission accuracy. It play a vital role in body stability, reliability and scalability.

This walking machine use rectangular body, both left and right sides of the machine arranged three legs, respectively (Fig. 3). Leg connects to body through a joint shaft. We use the symmetrical arrangement to ensure the machine's center of gravity coincides with the geometric center. In order to ensure the six-legged gait coordination in walking, we use a single motor to drive 6 legs movement synchronously. System power pass through the chain, specific delivery path are as follows: Motor output power pass through the sprocket 1, sprocket 2 to the shaft 2, then drive shaft 2 and shaft 3, respectively. In order to ensure the same speed of shaft 1, 2 and 3, the transmission ratio both of sprocket 3 and sprocket 5, sprocket 4 and sprocket 6 choose 1 preferably, use the same specifications of the chain to achieve constant speed drive.

ASSESSMENT AND TESTING

Assessment of virtual prototype: Virtual prototype is built on prototype systems or subsystems of the computer models. Compare to physical prototype, it have functional fidelity to a certain extent (Gladigau *et al*., 2012). In this study, we use virtual prototypes to replace physical prototypes to test and evaluate the design characteristics of the walking machine. We use Pro/ENGINEER for three dimensional modeling and import the model into the ADAMS for dynamic simulation and analysis, to verify the movements of the legs.

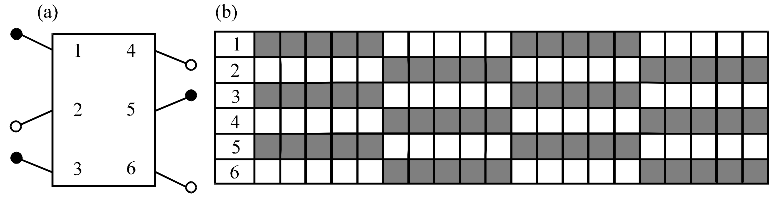

Fig. 2(a-b): (a) Arrangement of the legs and (b) Time plan for each leg

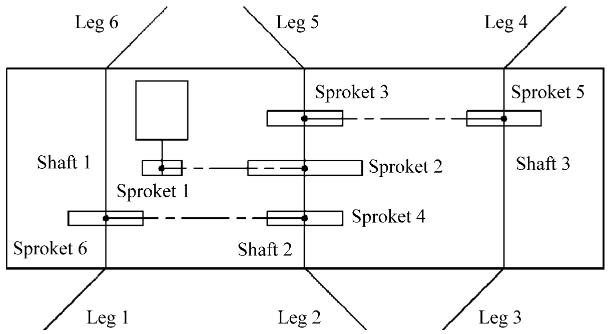

Fig. 3: Transmission system

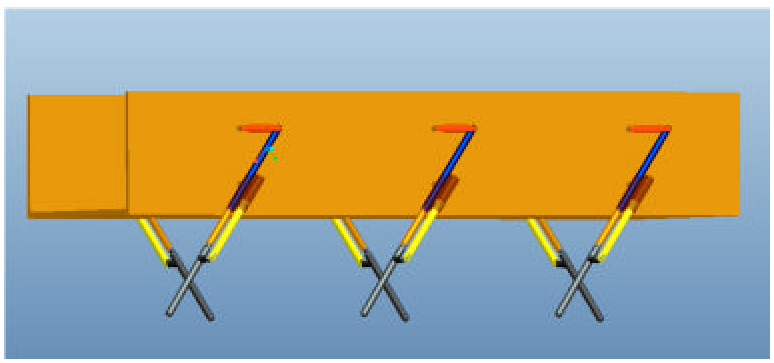

Fig. 4: View of three-dimensional model

By Pro/ENGINEER three-dimensional modeling, model diagram as shown in Fig. 4, import the modeling into ADAMS, the parts of the original model geometry does not change, but it needs to redefine the environment, material, add constraints and kinematic pairs and define the drive. Definition of gravity is vertically downward, component materials default is steel, plate floor was defined as concrete, Poisson's ratio 0.15, elastic modulus: 2.0×10^4 N mm^{-2}, density: 2.0 g mm^{-3}, the angular velocity of crank was defined as 5° sec^{-1}. Then we got the forward direction, height direction and lateral direction motion curve of the walking machine from ADAMS results, as shown in Fig. 5-7.

As shown in Fig. 5, in forward direction, this walking machine has a nearly constant speed, without any mutation. The model was not placed on the platform before the simulation begins, when the simulation begins, the model falls down on platform, so there is nearly 5 mm mutation in the first two seconds in Fig. 6. Overall, the change in height is less than 2 mm, it is negligible relative to the height of the machine. Figure 7 shows the motion curve in lateral direction of the walking machine. Due to the triangle gait, one side has single leg support, the other

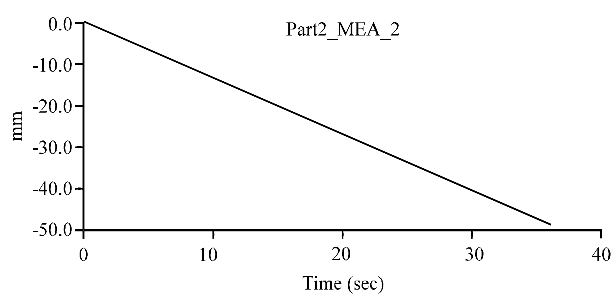

Fig. 5: Motion curve in forward direction

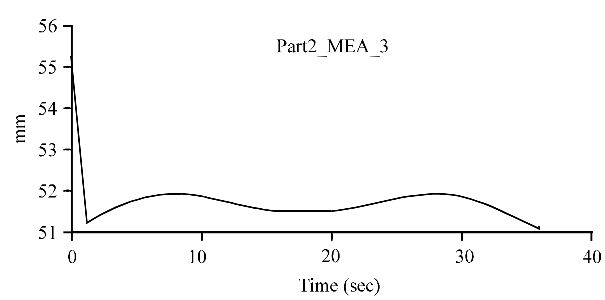

Fig. 6: Motion curve in height direction

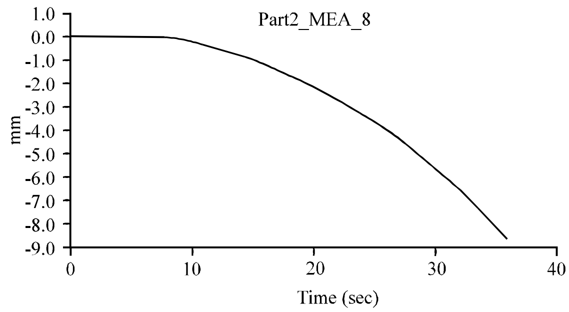

Fig. 7: Motion curve in lateral direction

side has two legs touching the ground, each side has different numbers of support leg, then produced a torque. When next group of legs touch the ground, the body will turn to the original direction slowly.

PHYSICAL PROTOTYPE TEST

The main purpose of the physical prototype testing in this study is to verify that the machine can realize the walking function. Secondly, by testing the basic characters of walking machine control part and the existing problems, the physical prototype testing provides a basis for the further improvement. The body portion of the entity prototype uses angle steel welding and leg structure are used C45E4 type steel processing, no heat treatment. Driven equipment selection Y150 DC gear motor, power 150 W, rated current 19.2 A, rated voltage of 12 V, the no-load speed 190 r min^{-1}, load cases speed is about 150 r min^{-1}, the output torque 50 kg cm^{-1}. Powered equipment used an ordinary car batteries. The physical prototype object is shown in Fig. 8.

After a no-load debugging, straight prototype testing conducted by The physical prototype. Straight line test sites for interior horizontal straight hard road, a length of 12.0 m. Average speed for each test is shown in Fig. 9, the relationship between average speed and crank turns is shown in Fig. 10.

In the same test environment, walking machine's right side was designated as the base level end, can be as the benchmark for measure (Left shift for positive, right shift for negative). We got the horizontal offset distance with the initial position after 12.0 m straight walking (Fig. 11).

These data above enable us to conclude that this walking machine's walking function is entirely achievable. As shown in Fig. 9, the speed of the physical prototype is stable. The data from test formed a tight cluster of points in Fig. 10 that illustrate the machine's motion law is stable, the trace deviation caused by skid. The offset in

Fig. 8: Physical prototype

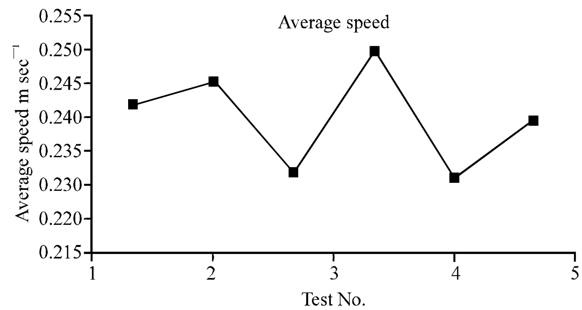

Fig. 9: Average speed for each test

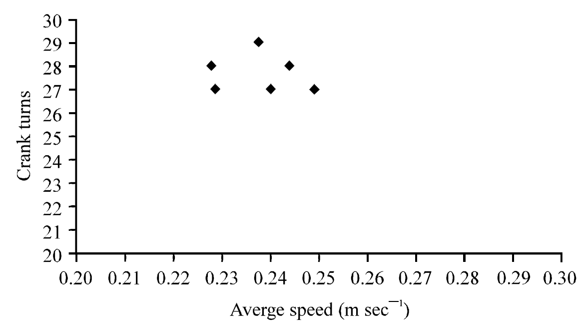

Fig. 10: Relationship between average speed and crank turns

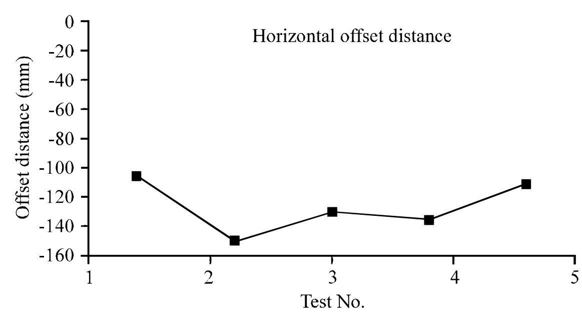

Fig. 11: Horizontal offset distance after 12.0 m straight walking

straight walking presents certain regularity, the range between 110-150 mm, mechanical process and assembly errors are mainly result in offset generated.

DISCUSSION AND CONCLUSION

Through the virtual prototype evaluation and the physical prototype test, the design of the six-legged walking machine walking function can be fully realized. In the virtual prototype evaluation, when the angular velocity of crank is 5° sec^{-1}, the speed of the walking machine is stable at 0.0135 m sec^{-1}. In the physical prototype testing, the speed of the walking machine is stable between 0.22-0.25 m sec^{-1}. Both in virtual prototype evaluation and physical prototype test, the machine center of gravity height jitter is tiny. The range of the center of gravity height jitter in virtual prototype evaluation is less than 2 mm. Horizontal offset distance shows an unexpected result, the offset distance range more than 110 mm but less than 150 mm. We believe it mainly cause by machine body incline which due to manufacturing errors of link 3.

Due to the adoption of tripod gait, it has a high requirement in leg phase accuracy when legs in turn to put up and down, or there will be a body sinks or leg stuck. The sprocket clearance in chain transmission lead to the transmission accuracy is not ideal, it will cause leg phase out of step. We will consider using turbo-worm gearing to resolve this problem, or choose other gait which is insensitive to leg phase accuracy.

The following conclusion can be drawn from the work of this study. Firstly, the six-legged walking machine walking function can be fully realized without control system. It is a meaningful characteristic if the machine needs to be deployed in radioactive hot spot. Secondly, for the whole walking machine, walking can be realized by enter a single rotary motion. Thirdly, the center of gravity height jitter of this machine can be neglected.

This six-legged walking machine shows a neoteric design to achieve walking movement, has a certain practical significance and reference value. We believe that the leg structure and the method in this study will help other researchers in walking machine designing.

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