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A design of leg-wheeled robot with reduced DOF and passive wheels

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Abstract– This paper presents a new type of leg-wheeled robot that is applied two design concepts. One is reducing DOF and the other is using passive wheels. By using these concepts, it is possible to design light weight robot. Since weight is one of the important problem to build up a robot which can stand for practical use. The new robot is designed for a mobile environment which has flat terrain and some kinds of obstacles such as steps or drain. Such environment can be observed in office or plants designed for human.

1. Introduction

Both the wheeled robot and walking robot are typically used as mobile mechanisms on the ground. These mechanisms have their own advantages and disadvantages. Although wheeled robot requires flat terrain, it is suitable for transportation at high speed with high energy efficiency. In difference, walking robot moves at lower speed and has poor energy efficiency compare to the wheeled robot. However, walking robot has excellent adaptability to the ground.

Taking the advantages and disadvantages of both the walking robot and wheeled robot into account, it is not difficult to get the idea to create a new mechanism by combination of the wheeled robot and the walking robot; leg-wheeled robot. On this point of view, there have been many kinds of studies on legged-wheeled robot. But, it is hard to say that almost all of the developed robots are in practical use. By the way, the main reason why walking robot is not in practical use is because it requires many numbers of degree-of-freedom (DOF), which leads to poor energy efficiency. Therefore, the addition of wheels to walking robot, which already has many numbers of DOF in the first place, will any increase the number of DOF and thus, making it more difficult to put it to practical use.

Hence, in order to overcome this problem, two kinds of concept have been proposed. The first one is reducing the DOF design. Generally, each leg of walking robot requires 3 DOF, therefore for quadruped robot, 12 DOF is required, and while for hexapod robot 18 DOF is required. Still, it is possible to reduce number of DOF for these robots, provided that enough attention is paid when designing the mechanism. By applying this concept, several robots have already been proposed [1].

Then, the other concept is using passive wheels. In case of the wheeled robot, one should at least require active joint. This fact causes of increase of robot weight. However, in case of leg-wheeled robot active joint is not always needed. Even if all of the wheels are passive joints, by the motion of the legs, the wheels can be use like as roller skating [2].

In view of these considerations, this study presents a new type of leg-wheeled robot which applies the above mentioned two concepts. The new robot is aimed to realize a mobile robot which can use in an environment designed for human activities. In concrete terms, office, factory and plants are the typical environment for the robot, because such environment consists of flats terrain and obstacles such as steps or drain. In such environment, high speed is expected for flat floor, and a function to stepping over obstacles.

2. Preparation of Papers

Fig.1 shows overview of the newly designed leg-wheeled robot that is applied the mentioned two concepts. The configuration of joints is clearly divided into two directions, horizontal direction and vertical direction. The robot has six legs in the vertical direction, and they are connected to hexagonal closed linkage in the horizontal direction.

The reason why the joint configuration is applied is based on the two concepts called GDA (Gravitationally Decoupled Actuation) and MDA (Motion Decoupled Actuation) [3], [4]. Notion of the first concept is to avoid energy loss that is generated by interference of actuations. Then, the notion of the second concept is to make a purpose of actuation clear. The above mentioned method satisfies these two concepts.

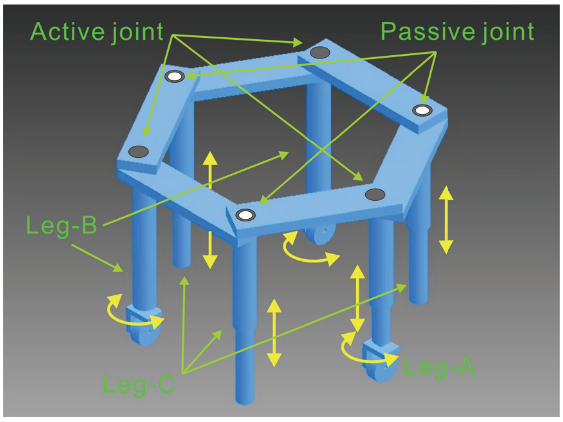

Fig.1 Overview of the leg-wheeled robot

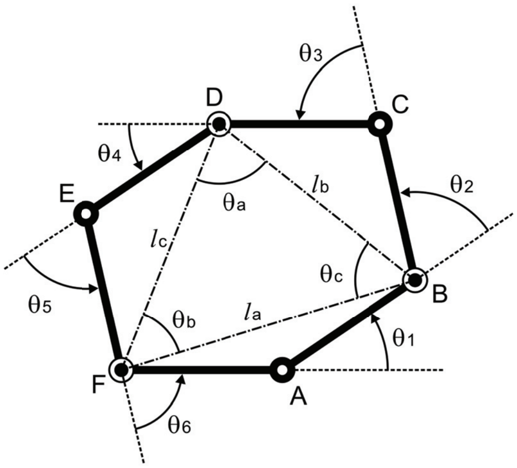

Fig.2 Definitions of hexagonal closed linkage

The hexagonal linkage has six joints, but only three joints are active joint and the others are passive joints. Since the length of all links is fixed, the shape of the hexagonal linkage is under control of the three active joints. This means that horizontal positions of six legs are controlled by the active joints in the hexagonal linkage, because every joint is placed on the vertex of the linkage.

Then, six vertical legs can be classified into three types; leg-A, leg-B and leg-C. Leg-A has one prismatic joint and one passive wheel, and number of this leg is only one. Leg-B has only passive wheel with no prismatic joint, and number of this leg is two. Then, leg-C has prismatic joint with no wheel, and number of this leg is three. Totally, three passive wheels and four prismatic joints are loaded on this robot. Here, the three wheels have active rotational joint around the vertical axis to control the direction of the wheels.

To summarize the above, total required number of active joints is 10. This number is less than that of quadruped robot which has typical mechanical design. Additionally, required power is very low for three joints of theses, because the three joints are only used to control the direction of the passive joints. On the other hand, the role of the three active joints in the closed linkage is to propel the hole of the robot to horizontal direction, and four active joints in the legs are used to switch the swing phase and the standing phase and to support body weight. Thus, enough power is required for these seven joints compared with the mentioned three joints.

3. Kinematics for closed linkage

Since the configuration of joints is separated into horizontal direction and vertical direction as mentioned above, we can also separate the kinematic into the closed linkage and vertical legs. Here, kinematics for the closed linkage is discussed.

Fig.2 shows model of the closed linkage and definition of parameters. In this figure, joint-A, C and E are active joints and joint-B, D and F are passive joint. Thus, joint angles θ_1, θ_3 and θ_5 are able to be observed, and joint angles θ_2, θ_4 and θ_6 are not. Then, method to seek θ_2, θ_4 and θ_6 from θ_1, θ_3 and θ_5 will be discussed from now.

Here, the length of every links is defined as same length L. In this case, la can be sought by the following equation, because ΔABF is an isosceles triangle.

$$la = 2L\cos\frac{\theta_1}{2}$$

Similarly,

$$lb = 2L\cos\frac{\theta_3}{2}$$

$$lc = 2L\cos\frac{\theta_5}{2}$$

By applying cosine theorem on ΔBDF,

$$\theta_c = \mathrm{Cos}^{-1}\frac{\cos^2\frac{\theta_1}{2} + \cos^2\frac{\theta_3}{2} - \cos^2\frac{\theta_5}{2}}{2\cos\frac{\theta_1}{2}\cos\frac{\theta_3}{2}}$$

$$\theta_a = \mathrm{Cos}^{-1}\frac{\cos^2\frac{\theta_3}{2} + \cos^2\frac{\theta_5}{2} - \cos^2\frac{\theta_1}{2}}{2\cos\frac{\theta_3}{2}\cos\frac{\theta_5}{2}}$$

$$\theta_b = \mathrm{Cos}^{-1}\frac{\cos^2\frac{\theta_5}{2} + \cos^2\frac{\theta_1}{2} - \cos^2\frac{\theta_3}{2}}{2\cos\frac{\theta_5}{2}\cos\frac{\theta_1}{2}}$$

From these result, θ_2, θ_4 and θ_6 can be found from the following equations.

$$\theta_2 = \pi - \frac{\theta_1 + \theta_3}{2} - \theta_c$$

$$\theta_4 = \pi - \frac{\theta_3 + \theta_5}{2} - \theta_a$$

$$\theta_6 = \pi - \frac{\theta_5 + \theta_1}{2} - \theta_b$$

Therefore, forward kinematic of the robot can be solved from these joint angles by using typical type of serial link manipulator.

4. Method of mobile

4.1. Walking mode

At first, the manner when this robot is used as the walking robot is discussed. Although speed in this mode is lower than the speed of roller skating mode (this mode will be discussed after), this mode can perform high adaptability to the terrain such as stepping over motion. Basically, roller skating mode is used for moving on flat floor, but walking mode is also available for flat floor.

4.1.1. Basic gait manner

For the proposed robot, it is impossible to apply conventional gait for conventional walking robot. Thus, original gait manner must be considered for our robot. The most important point for this gait study is pay attention for the static stability.

To discuss new gait, it is required to define some terminologies as follows.

H-leg (Holding leg) : A leg that has no passive wheel; leg-C in **Fig.2**. In other words, the sole of leg can hold ground without slip.

S-leg (Sliding leg) : A leg that has passive wheel; leg-A or B in **Fig.2**. In other words, sliding motion is allowed for this leg.

semi-standing phase : A moment or state in which position of S-Leg is contacting to the fixed point.

semi-swing phase : A moment or state in which position of S-Leg is relatively moving on the ground.

For walking robot, every leg must usually repeat two modes, standing phase and swing phase. The Semi-standing phase and the semi-swing phase correspond to the two modes. Although vertical joint is required to switch the two modes, this joint is not required by using passive wheels in this robot.

Basic gait of our robot is realized by the following simple motion. One of three H-legs should make swing phase one by one and moves to the next contact point to the ground. The shape of the body is transformed by repetition of the simple motion, and the body is propelled.

This sequence is explained by **Fig.3**. In this figure, A, C and E are S-legs, and B, D and F are H-legs. The aim in this example is to move the contact point of leg-D from point D to pint D'.

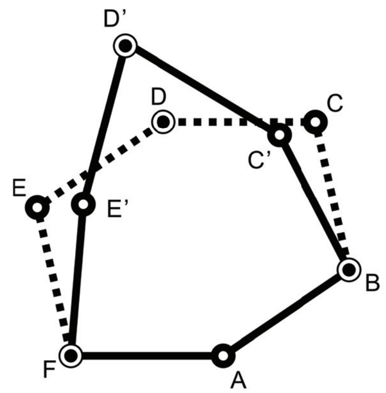

Fig.3 Example to decide the contact point

To perform it, leg-B and F must in the standing phase, which means the position of B and F is fixed. Thus, since position of A is fixed, leg-A is in the semi-standing phase automatically. This means position and orientation of link AF and AB is fixed. In this situation, the position of D can be moved to D' by changing the shape of the closed linkage. Then, leg-C and D is in semi-swing phase in this time. By applying the same manner, the position of B and F can be moved in order, the robot can move forward.

4.1.2. Planning of contact points

Here, we think about to seek suitable contact point, when robot makes rotation around a center position. This calculation can also apply to the straight walking by set the center position enough far away. On the contrary, if center position is inside of the body, turning on the spot can be performed. The target of the contact point can be calculated by the following equation.

$$x_i^* = r_i \cos(\theta + \emptyset) + x_0$$

$$y_i^* = r_i \sin(\theta + \emptyset) + y_0$$

$$\emptyset = \mathrm{arctan2}(y_i - y_0, x_i - x_0)$$

Here, meanings of the other parameters are as follows.

x_i, y_i : position of leg i

x_0, y_0 : center position of rotation

In the equation, θ means an angle of rotation in a step. Actually, it is not suitable to decide θ directly. θ should be considered with stroke length l_s by using the following equation.

$$\theta = \frac{l_s}{r_i}$$

We can decide the stroke length l_s based on the workspace of the robot.

4.2. Stepping over obstacle

Method to step over obstacle is described in this section. As mentioned above, one leg of the legs which has passive wheel has a prismatic joint. This joint is not required for the movement on flat terrain, but it is required to step over motion.

The sequence of stepping over is explained in **Fig.4**. Here, three yellow legs mean legs which have no passive wheel, two blue legs mean legs which has passive joint without vertical joint, and one red leg means leg which has both of passive wheel and vertical joint.

In this sequence, required additional joint for S-leg is only one. However, it is not useful, because the direction of the body is limited when robot goes in to a step. If remaining two legs (blue legs) have additional vertical joint for each, it makes easy to access to steps.

4.3. Roller skating mode

Roller skating mode is used for movement on the flat floor, which can perform high speed movement. To use this mode, height of leg-C must be adjusted to be shorter than that of the leg-A and leg-B. Then, height of leg-A must be adjusted to be the same height of leg-B. In brief, the robot must be supported by the three legs with passive wheels.

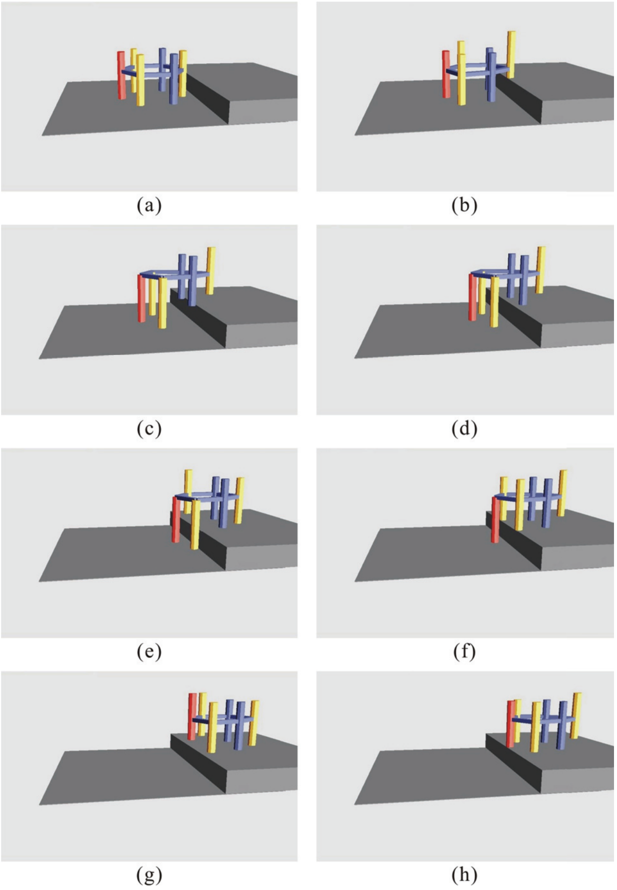

Fig.4 Sequence of stepping over motion

5. Prototype models

Fig.5 shows first prototype model which is applied the proposed design. The length of the vertical leg is 125mm and each arm of the hexagonal body is 80mm. RC servo motors are applied for all joints. Since roller skating mode is not under consideration in this model, ball casters are used as the passive wheel. In case of the ball caster, three small active joints to drive the passive wheels about vertical axis are not required, but roller skating mode is not realized by this model. The results of this model are discussed in the past work [5].

Then, **Fig.6** shows second prototype model which is designed to confirm the roller skating mode. The length of each arm of the hexagonal body has 105mm. This model performed skating with about 30mm/s speed in our first simple experiment.

6. Conclusion

In this study, we have proposed new type of leg-wheeled robot by using two important concepts to realize practical mobile robot. The robot is available for moving on environment designed for human activities. Basic performance has been presented in the experiment by using prototype model. Our next target is to discuss about the specification of skating mode and to realize the final

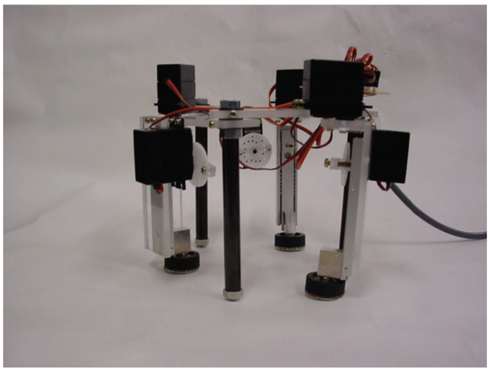

Fig.5 Overview of the first prototype model

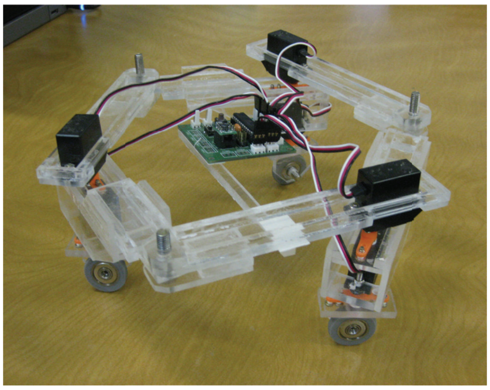

Fig.6 Overview of the second prototype model

model based on the **Fig.1** by combination of the two prototype models shown in **Fig.5** and **Fig.6**.

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