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Leg Mechanism Design for SLIP Model of Hydraulic Quadruped Robot

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Abstract - The Spring Loaded Inverted Pendulum (SLIP) describes the dynamic walking of humans and animals in a simplified manner. However, realizing such movements by means of a combination of typical articulated legs and linear actuators has some limitations. This paper proposes a leg mechanism that accurately reflects the SLIP based on its mechanical constitution. The SLIP design based leg is able to do decoupled swing motion and extension motion. Also this study has focused on improving the straightness of extension motion.

Keywords - Quadruped robot, Mechanism design, SLIP

1. Introduction

Quadruped robots possess structures similar to those of four-legged animals, and they easily adapt to rough terrains and environments such as mountains. Consequently, numerous studies on such robots are currently being conducted in terrains that are inaccessible to wheel- or caterpillar-based vehicles. In particular, BigDog and AlphaDog developed by Boston Dynamics have been demonstrated to have the mobility and ability to carry large masses, which are traits useful during military or disaster relief tasks.[1]

The Spring Loaded Inverted Pendulum (SLIP) is commonly used to analyze and control the dynamic walking and running of humans and animals. In the SLIP, a point mass, with the entire body mass concentrated at its center, and massless springs are connected to a pivot joint.[2, 3] Various movements can be realized by performing swing motions around the joint and extension motions based on the compression and extension motion of the spring.

Telescopic legs using linear actuators are the simplest forms of legs for walking robots realized on the basis of the SLIP. M. Raibert studied a walking robot that has a linear actuators as its leg. A relatively simple algorithm can control the SLIP model-based legs.[4, 5] Repeated contacts with the ground, however, negatively affected the durability of the actuator and sensor, and the motion range was limited by the actuator's stroke. Many researchers have attempted to implement the SLIP-based articulated leg in different ways to overcome these problems.

The well-known hydraulic robots are HyQ of the IIT, BigDog of Boston Dynamics, and JINPOONG of the Korean Institute of Industrial Technology.

In HyQ, a leg with three degrees of freedom (DOF) is implemented by using a linear actuator coupled with a four-bar mechanism, and a virtual spring extending from the hip joint to the foot-tip was implemented by means of joint torque control. Furthermore, the variable stiffness implemented by means of joint torque control has the advantage that it can be easily controlled by software.[6]

Fig. 1 CAD design of the proposed leg. Among the three DOF, only two DOF, excluding adduction and abduction, are implemented by means of two hydraulic linear actuators.

BigDog and JINPOONG have the same actuator configuration as HyQ and the same structure of redundant DOF. Additionally, the SLIP was implemented in these robots by mounting passive springs and position control of the linear hydraulic actuator.[7]

Such modification can serve as a shock absorber, as in the case of the springy leg in the SLIP, and as energy storage. However, the leg may be unstable during the supporting stance, and extension motion along a straight line can be affected by the performance of the joint control.

In the SLIP model, extension motion cannot easily be realized by means of leg-like structures with several pivot joints. The straight line movement of the endpoint when the pivot joints are combined depends on each joint's performance of position control. Rectilinear motion may not be achieved by pivot joints implemented with a linear hydraulic actuator, in particular, owing to the nonlinearity of the torque and the delayed response.

In the case of AlphaDog and Baby Elephant of SJTU[8], attempts were made to solve these problems related to the articulated leg mechanically. Even though the

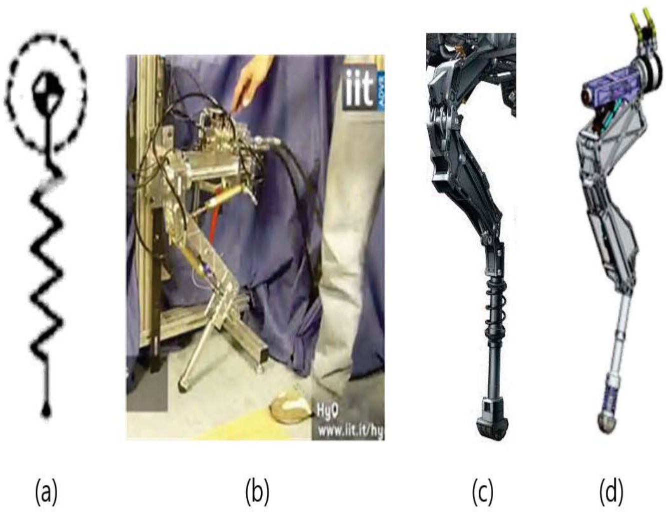

Fig. 2 (a) General SLIP template (b) Leg of Hy-Q (c) Leg of BigDog (d) Leg of JINPOONG

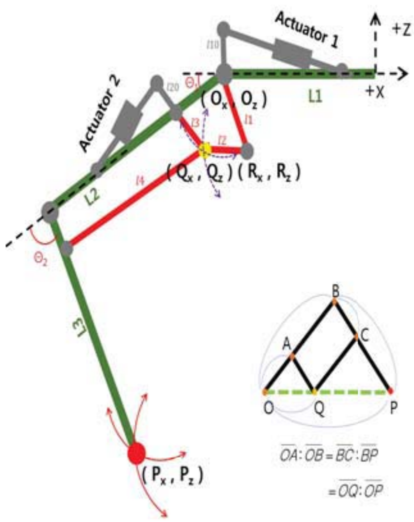

Fig. 3 Assumed leg structure of AlphaDog and pantograph ratio

legs of these two robot models look different, the pantograph mechanism was applied to both, thus endowing them with the mechanical properties that can help realize the extension motion with only one linear actuator.

Thus, these robots differ from the conventional walking robots that employ serial and articulated legs and realize the extension motion by employing control and algorithms.

Most of the walking robots thus developed realize walking motions by coordinating several pivot joints. In order to achieve high performance with these legs, however, complex control algorithms and sensor systems are necessary.

This paper proposes a leg mechanism that mechanically realizes swing and extension motions on the basis of the SLIP; the validation of this mechanism through simulation and experiment is also described in the paper.

2. Design the Leg

2.1 Related Work

The motions of AlphaDog, the state-of-the-art SLIP-based hydraulic walking robot, are based on swing and extension. Although the structure of AlphaDog is not yet known completely since it has not been described in any published paper, video and image analyses show that it accurately reflects the SLIP model structure.

Each of the two actuators in AlphaDog is used to generate swing and extension motions, and they are believed to function by means of the pantograph. A pantograph is a four link structure and is often used in machining tool or carving machine because it can enlarge or reduce its imitated motion at a certain ratio. Additionally, decoupled motion becomes possible with respect to different inputs; hence, pantographs are used in leg mechanics of gravitational decoupled actuators (GDA).[9-11]

The fig.3 shows the speculated leg structure for AlphaDog. The structure can be divided into the motion-generating part and the pantograph that amplifies the generated motion. According to the characteristics of the pantograph, the motion of joint Q, where three links, l_2, l_3, and l_4 meet, is amplified by the pantograph ratio and realized at the endpoint P at the foot. The pantograph ratio can be described as,

$$L_2 - l_4 : L_2 = l_3 : L_3$$

$Actuator_1$ located at L_1 is connected to l_1 to generate swing motion, and $actuator_2$ located at L_2 is connected to l_3 to realize the extension motion. If $actuator_2$ is fixed, the pantograph and the motion-generating parts also are fixed by l_3, which is connected to $actuator_2$, and hence, they move as a single body. That is, if $actuator_1$ is initiated, all links below the hip joint point O begin to rotate identically about the point, and thus, the swing motion is realized. In contrast, if $actuator_1$ is fixed, l_1 that is connected to it is also fixed. Thus, when $actuator_2$ is initiated, point Q starts rotating around point R that connects l_1 and l_2. Thus, motion with uniform curvature is generated in all cases, as shown in the fig.3.

If the pantograph ratio or length of l_1 and l_2 in the motion-generating part is infinitely incremented, the effects of such curvature can be eliminated. In other words, AlphaDog cannot generate straight motion based on the mechanism in which two links are used to generate the motion. Hence, to solve this problem, $actuator_1$ must be adjusted to compensate the straightness error caused by the curvature during the extension motion.

This paper proposes a leg mechanism that assures extension along a straight line using one actuator by applying a straight line generating mechanism to the motion-generating part.

Traditional straight line generating mechanisms include Chebyshev linkage, Watt's linkage, and Peau-

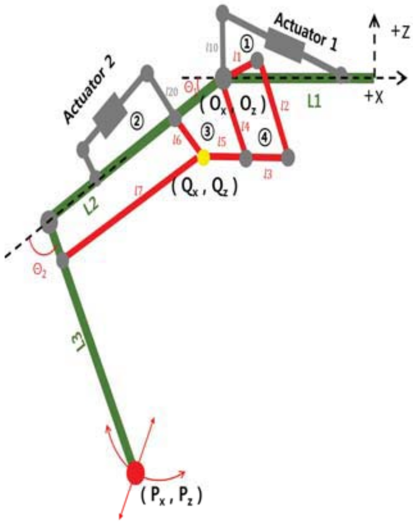

Fig. 4 Structure of proposed leg mechanism.

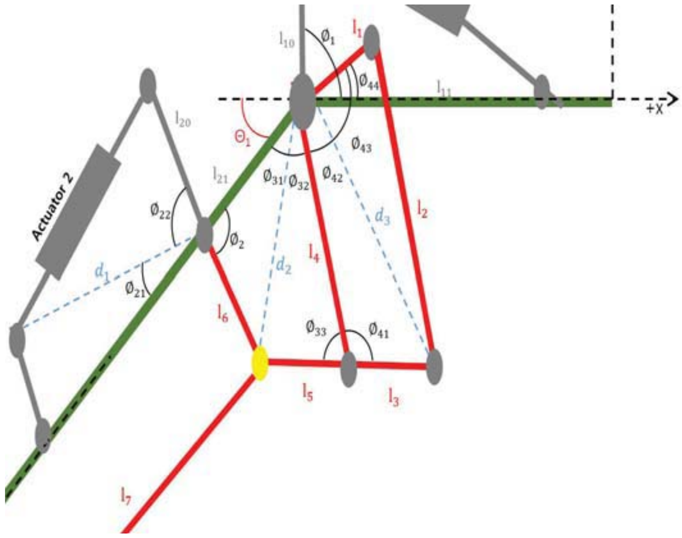

Fig. 5 Detailed view of proposed leg mechanism with definition of parameters for forward kinematics used in (1) to (26)

cellier–Lipkin linkage. Among these mechanisms, the straight line generating mechanisms derived from Chebyshev linkage have been employed and studied for various types of mechanics because these mechanisms have relative simple structures and can decrease the overlapping of links during the motion.[11]

The leg that has a straight line generating mechanism applied to its motion-generating part is illustrated in the fig.4. Point Q that connects the motion-generating and pantograph parts is always located somewhere along the straight line that connects the hip joint and the foot-end, and it performs extension motion by using $actuator_2$. As in the case of AlphaDog, all links below the hip joint become fixed for swing motion when $actuator_1$ operates.

Each of the two motions is solely affected by one actuator, and therefore, the two motions do not interfere with each other. That is, swing and extension motions are fully decoupled, and this can be confirmed from the workspace shown in the fig.7.

2.2 Kinematics

In this novel leg mechanism, θ_2 is only affected by $actuator_2$, while θ_1 is affected by both $actuator_1$ and $actuator_2$, unlike conventional serial link structures, where the rotational position of a joint is affected only by one actuator. In order to obtain the endpoint position of the leg, θ_1 is calculated based on θ_2 which can be calculated using $actuator_2$ stroke.

The kinematics of the proposed leg mechanism can be explained in four stages as shown in fig.4.

Stage 1 involves analysis to determine ϕ_1 and ϕ_{44} according to $actuator_1$'s stroke, where ϕ_{44} is the angle between L_1 and l_1, while l_{10} and l_1 are designed to always form an angle of $71°$ with each other.

$$\cos\phi_1 = \frac{l_{10}^2 + l_{11}^2 - act_1^2}{2 \cdot l_{10} \cdot l_{11}} \tag{1}$$

$$\phi_1 = \arctan(\frac{\sin\phi_1}{\cos\phi_1}) \tag{2}$$

$$= \arctan(\frac{\pm\sqrt{1-\cos^2\phi_1}}{\cos\phi_1}) \tag{3}$$

$$\phi_{44} = \phi_1 - 71° \tag{4}$$

d_1 and ϕ_{21} in stage 2 are always values fixed by design values, and ϕ_2, which is the angle between l_{21} and l_6, can be determined. Since the pantograph mechanism used in the leg structure includes a parallelogram, θ_2 formed by L_2 and L_3 can be easily computed using ϕ_2.

$$d_1 = 230.8679mm \tag{5}$$

$$\phi_{21} = 4.9697° \tag{6}$$

$$\cos\phi_{22} = \frac{d_1^2 + l_{20}^2 - act_2^2}{2 \cdot d_1 \cdot l_{20}} \tag{7}$$

$$\phi_{22} = \arctan(\frac{\pm\sqrt{1-\cos^2\phi_{22}}}{\cos\phi_{22}}) \tag{8}$$

$$\phi_2 = \phi_{21} + \phi_{22} \tag{9}$$

$$\theta_2 = \pi - \phi_2 \tag{10}$$

In stages 3 and 4, angles formed by the links in the motion-generating parts can be calculated, and then, these values are used to find θ_1. This calculation is based on the fact that the sum of ϕ_{33} and ϕ_{41} is $180°$ since l_3 and l_5 form a link.

$$d_2 = \sqrt{l_{21}^2 + l_6^2 - 2 \cdot l_{21} \cdot l_6 \cdot \cos\phi_2} \tag{11}$$

Table 1 Parameters for kinematics of proposed leg.

Link	Length [mm]	Link	Length[mm]
L_1	400	l_{20}	35
L_2	400	l_{21}	230
L_3	400	l_3	50
l_1	104	l_4	114
l_{10}	45	l_5	113
l_{11}	230	l_6	80
l_2	80	l_7	320

$$\cos\phi_{31} = \frac{d_2^2 + l_{21}^2 - l_6^2}{2 \cdot d_2 \cdot l_{21}} \tag{12}$$

$$\phi_{31} = \arctan\left(\frac{\pm\sqrt{1-\cos^2\phi_{31}}}{\cos\phi_{31}}\right) \tag{13}$$

$$\cos\phi_{32} = \frac{d_2^2 + l_4^2 - l_5^2}{2 \cdot d_2 \cdot l_4} \tag{14}$$

$$\phi_{32} = \arctan\left(\frac{\pm\sqrt{1-\cos^2\phi_{32}}}{\cos\phi_{32}}\right) \tag{15}$$

$$\cos\phi_{33} = \frac{l_4^2 + l_5^2 - d_2^2}{2 \cdot l_4 \cdot l_5} \tag{16}$$

$$\phi_{33} = \arctan\left(\frac{\pm\sqrt{1-\cos^2\phi_{33}}}{\cos\phi_{33}}\right) \tag{17}$$

$$\phi_{41} = \pi - \phi_{33} \tag{18}$$

$$d_3 = \sqrt{l_3^2 + l_4^2 - 2 \cdot l_3 \cdot l_4 \cdot \cos\phi_{41}} \tag{19}$$

$$\cos\phi_{42} = \frac{d_3^2 + l_4^2 - l_3^2}{2 \cdot d_3 \cdot l_4} \tag{20}$$

$$\phi_{42} = \arctan\left(\frac{\pm\sqrt{1-\cos^2\phi_{42}}}{\cos\phi_{42}}\right) \tag{21}$$

$$\cos\phi_{43} = \frac{d_3^2 + l_1^2 - l_2^2}{2 \cdot d_3 \cdot l_1} \tag{22}$$

$$\phi_{43} = \arctan\left(\frac{\pm\sqrt{1-\cos^2\phi_{43}}}{\cos\phi_{43}}\right) \tag{23}$$

$$\theta_1 = \pi - \phi_{31} - \phi_{32} - \phi_{42} - \phi_{43} - \phi_{44} \tag{24}$$

Finally, θ_1 and θ_2 are computed to solve the forward kinematics of the two-link structure. The leg endpoint thus calculated is as follows.

$$P_x = O_x + L_2\cos(\theta_1) + L_3\cos(\theta_1+\theta_2) \tag{25}$$

$$P_z = O_z + L_2\sin(\theta_1) + L_3\sin(\theta_1+\theta_2) \tag{26}$$

The next section describes the workspace calculated based on the kinematics and straightness of the extension motion through simulation and experimental results obtained for an actual manufactured leg.

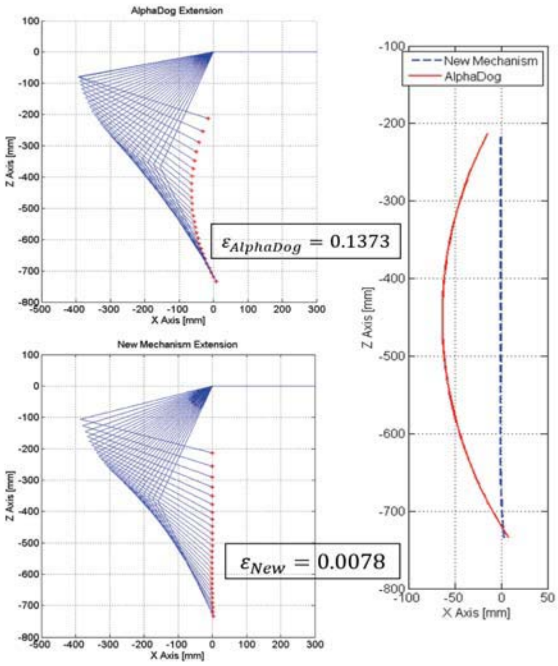

Fig. 6 Simulation results of assumed AlphaDog leg and proposed leg for straightness of extension motion.

3. Simulation and Experiments

As mentioned in Section 1, designing the SLIP-based articulated leg's endpoint to have rectilinear trajectory is rather a difficult task. As the quadruped robot trots with its two feet on the ground, a rotational force acts on the body, or an unstable posture is caused by the shift of the body's center to its left, right, front, or back. Hence, achieving the straightness of an extension motion can be considered as a performance index for the leg mechanism that focuses on both swing and extensions motions.

The error in the straight-line movement via extension motion, epsilon, is considered as an important performance indicator for the leg mechanism, and epsilon is defined as follows.

$$\epsilon = \frac{P_{x,max} - P_{x,min}}{P_{z,max} - P_{z,min}}$$

Even though the proposed leg mechanism comprises several pivot joints, the straight line movement via extension motion is guaranteed mechanically. The formulation of this mechanism is influenced by AlphaDog, but it yields better results.

Figure6 shows the simulation results to compare the extension motions of AlphaDog and the proposed mechanism. The dimensions of AlphDog's structure used in the simulation were assumed as mentioned previously. Thus, the ϵ described earlier does not have much significance in this case. Nonetheless, what we intended to show was that AlphaDog's extension motion is limited by the motion-generating part comprising two links, as mentioned in

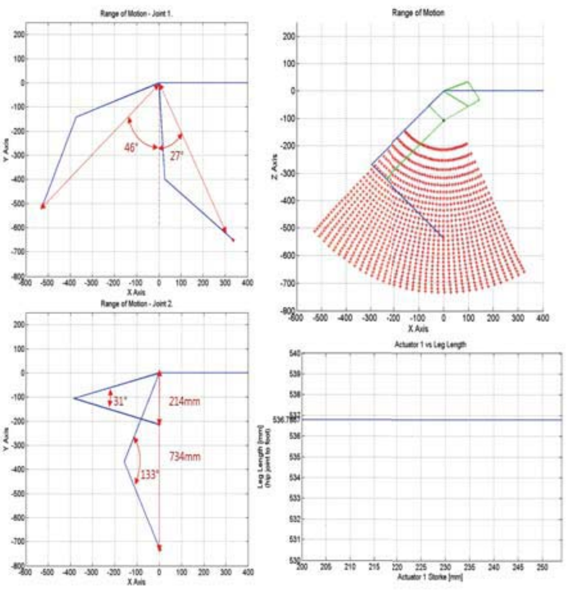

Fig. 7 Workspace of proposed leg. Simulated wiht actuation stroke 227±27mm

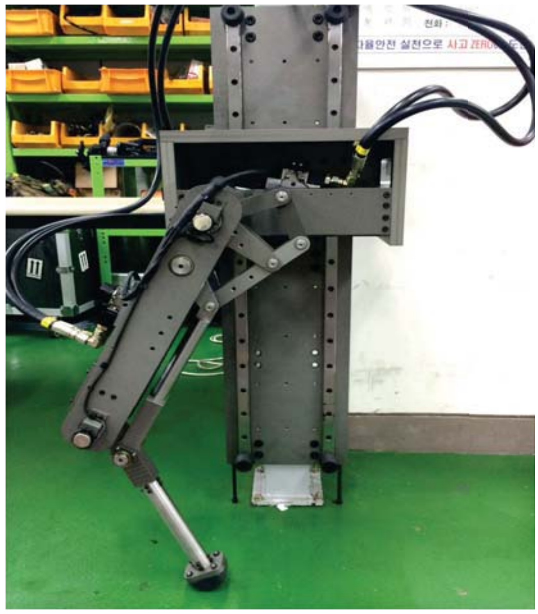

Fig. 8 Picture of 1DOF test bench for leg prototype.

Section 2.

Figure7 shows the workspace of the designed leg. The strokes of two linear actuators used to drive the legs are of 227±27 mm, and the graphs show results for the condition when $actuator_1$ and $actuator_2$ are initiated independently as well as together. When only $actuator_1$ is initiated, $-46° \sim +27°$ of motion range is imposed in reference to the virtual line connecting the hip joint and the foot-tip. Moreover, the distance between the hip joint and the foot-tip is fixed regardless of the leg's swing angle. Based on these results, we know that the swing and extension motions of the proposed mechanism are completely decoupled. If only $actuator_2$ is initiated, the included angle between L_2 and L_3 has a range of $107°$. In this case also, the movement of $actuator_2$ does not affect the swing motion, showing a completely rectilinear trajectory. Figure8 shows the actual manufactured leg. Among the three dof, only two dof, excluding adduction and abduction, are implemented, and limited by using a linear guide for motion along the z-axis only.

4. Conclusion

This paper investigated a leg mechanism that is based on swing and extension motions of the SLIP model. As AlphaDog, it has three DOF and an actuator configuration which uses a pantograph and two linear hydraulic actuators to perform decoupled swing and extension motions. Here, the ability to realize straight-line movement via extension was improved by using a straight-line generator, which is expected to be a major advantage in controlling the legs during stance.

The simulation result shows better straight-line movement via extension than that in the case of AlphaDog. However, the positive impact that this result will have on actual walking is unknown. Henceforth, based on the results of this study, further studies will be conducted to determine the effects of straight-line movement via extension on actual walking and to accordingly develop an appropriate controller design.

Acknowledgement

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