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Parallelogram linkage leg structure for stabilized walking gaits in humanoid robot

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ABSTRACT

The utilization of parallelogram structure in a small-sized humanoid robot consists of two parallel platforms that are linked serially in each leg. The thigh and shank of each leg consists of two servomotors as actuator and linked in parallel platform. By using parallel mechanism in leg structure, foot sole surface is always parallel to the walking surface at any point. Even it looks unnatural to human-like walking motion, the expected result is the robot can maintain it posture while walking and at the point foot sole touch the walking surface, unnecessary vibrates can be modulated at the certain level to remain its balance. The effectiveness and the performance of the proposed parallel platforms are experimented by using zero moment point (ZMP) method by taking various scenario data from pressure sensors attached at the footsole. Planned walking gait is introduced to be identical in terms of foot steps length and width of each leg swing. As the results, in terms of load in each actuator, required torque at servomotors can be reduced because two servomotors are used simultaneously in one parallel system. Stable walking gait can be predicted as the quantity of error falls within the error ranges from the published walking gait patterns.

1. Introduction

The development of two-legged humanoid robot provide mobility that would allow robot to mix and socialise in harmony with people [1]. Compare with wheeled humanoid robot, bipedal robot promote natural interaction interface that create accessible environment for human to approach the robot [2]. However, the problem with humanoid robots that use two-legs for walking is how to achieve balanced and stabilized walking movement which required high-rigidity structure and sufficient actuator force leg-design [3]. The bending of leg structure's frame and inability to generate sufficient force to support the body should be prevented to accomplish basic mobility task.

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David Gouaillier *et. al*. [4,5] developed small-sized Humanoid Robot called NAO which have lighter body and uitilize less powerful motor. This robot is less dangerous in human environment and less subject to breakdown. Some of the researches [6] use parallel-link leg structure in humanoid robot to optimize the force from actuator for stable walking gaits. The result shows less torque is necessary in parallel link active joints than that in serial biped robot. However, the usage of linear actuator is heavier, costly than servomotor and robot appearance do not look like human being because removal of knee structure from the initial design. Jeakweon Han and Dennis Hong [7] used spring assisted parallel four bar linkages for CHARLI-E Robot. The parallel-link leg design made the robot lighter and has lower cost for actuator parts.

In this paper, the proposed parallel-linkage leg structure able to reduce torque load on each servomotor and suggest an optimized solution for the design. Then, the design is evaluated by utilizing servo-positioned torque measurements and Zero-Moment Point (ZMP) method [8] to analyze whether balanced walking gaits can be achieved.

2. Hardware Specification

2.1 Robot Specification

Kondo KHR-2HV, a Japanese-manufactured small-sized humanoid robot which is used in small-sized humanoid robot competition in Japan has been used in this research because of its experimental capability to perform walking gaits. This robot size is 390[mm] height and 190[mm] width. Total mass is 1.42[kg] include a Ni-MH battery. The robot appearance is shown in Figure 1.

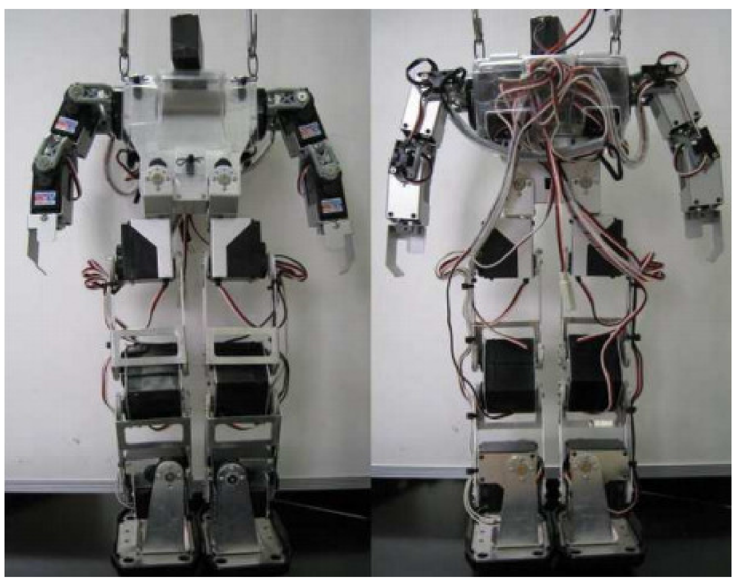


Fig. 1. KHR-2HV appearance

The specifications for the robot are shown in Table 1. The robot has been modified to increase degree of freedom (DOF) in the knee parts. Upper body consists of head; arms and trunk with altogether have 7 degrees of freedom (DOF).

Table 1
KHR-2HV Specifications

Size (mm)	116 X 190 X 390 (L X W X H)
Weight (kg)	1.42
Degrees of Freedom	19 (Upper body ; 7, Leg : 6 x 2)
Control Board	RCB-3J

USB interface is used to connect this robot to PC for writing program into control board. This robot uses KRS-788HV Red Version servomotors as actuator and these actuators are used to move all body parts of the robot. This servomotor can produce high output torque of 10 kgf· cm and maximum speed 0.14 s/60°.

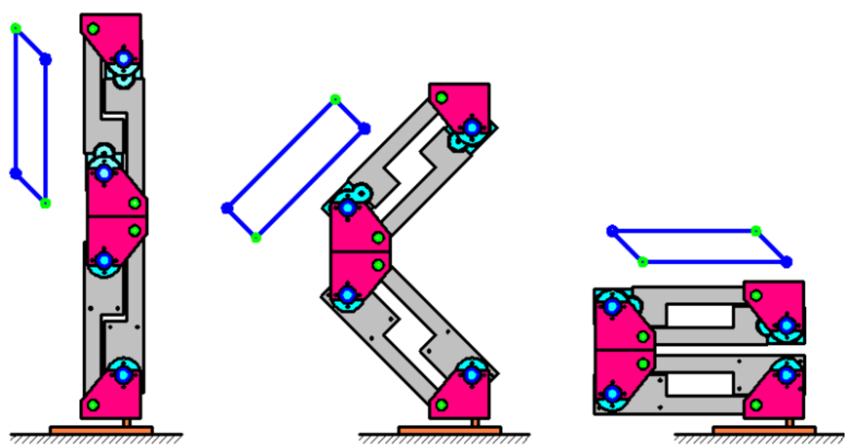
2.2 Parallel Linkage Leg Design

The proposed parallel mechanism for this robot which each leg composed of two parallel platforms as a thigh and a shank (Figure 2). In general, most humanoid robots developed so far walk stably by bending their knee joints. This is due to the fact that controlling the Zero Moment Point (ZMP) becomes quite difficult when the knee joint is stretched [9] [10].

Then, the thigh and shank is designed so that their lengths are identical to easily adjust robot's center of mass. These can prevent center of mass dislocated when moving and can make this robot become more stable even walking dynamically.

The main reasons using this parallelogram four-bar linkage is as follows;

i. Forces to support body weight are reduced and high efficiency can be achieved.
ii. Foot sole already parallel to the planar surface so that the robot will automatically maintaining its body position

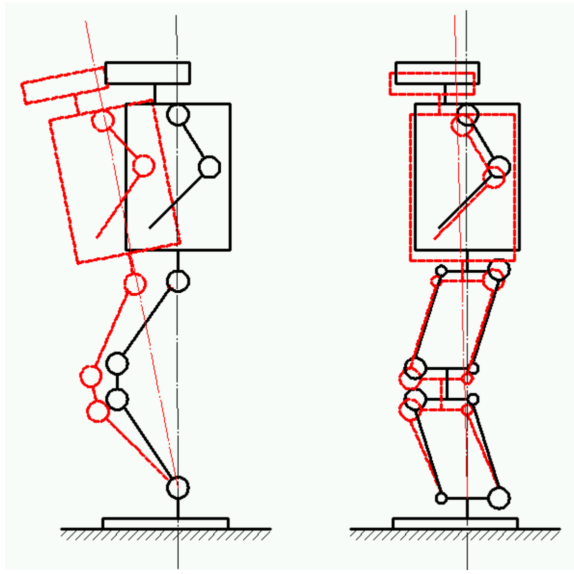


(a) (b) (c)

Fig. 2. Parallel linkage leg structure in (a) Elongates, (b) Middle-stand (c) Squat condition

2.3 Parallel-link Leg Characteristics

By using parallel mechanism leg structure, foot sole surface is always parallel to the walking surface at any point. Even it looks unnatural to human-like walking motion, the expected result is that the robot can maintain it posture while walking and at the point foot sole touch the walking surface, unnecessary vibrates can be reduced.



(a) Serial link (b) Proposed Parallel link leg

Fig. 3. Difference between two leg structures

Humanoid robot's center of gravity position would change if there is small angle displacement at the ankle joint. Thus, in serial-link leg structure, controlling robot's center of gravity to move stably require precision control at the ankle joint Therefore, using parallel-link mechanism in shank structure, even the robot is in unbalanced condition, it can be controlled mechanically using parallel-linkage structure which has high rigidity.

2.4 Torque on Actuator

Figure 4 shows torque at each servomotor in robot's legs structure. Assuming torque,T and r is length of the link, torque calculation can be shown as;

$$T= r \times F\sin\vartheta \qquad (1)$$

Assuming that leg-structure is static and maximum torque, when leg structure is perpendicular to the walking surface (sin 90°=1) is calculated. At this point, knee part is totally bent and comparision of this parallel structure leg to serial structure leg is made.

2.5 Torque Load on Servomotor

Electric current on servomotor changes [11] when robot is moving or maintain certain posture due to signal delivered from the control board. Thus, sufficient torque is required to make sure the servomotor rotates to its desired angle at the right speed and allowable respond time to enable execution of the robot movement and walking gaits. The torque on servomotor could be indicated by how much current flow on each servomotor. The relation of motor torque in servomotor and current can be shown in Eq. (2)

$T = Kt*I$ (2)

For experiment, 1 parallel linkage platform consists of 2 active servomotors are stretched from 0° to 90° while the data of the current is taken using current sensor, Allegro ACS715. This sensor is used because the total output error is small about 1.5% at temperature T=25°. These two active servomotors are located at knee (S_3) and ankle (S_4) respectively. The data from current sensor is processed using H8/3069F A/D Converter and sent to laptop environment for reading. To get the precise reading the noise is eliminated and the data is averaged.

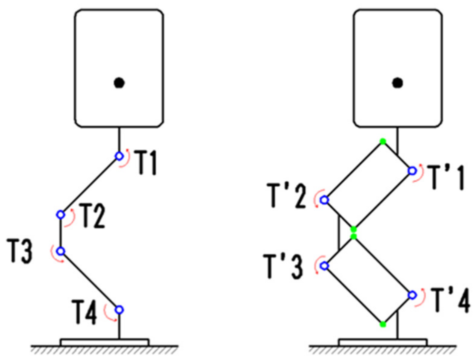


Fig. 4. Servomotor arrangement in sagittal plane

3. Results and Discussion

3.1 Torque in Parallel Linkage Leg

Torque for knee (S_3) and ankle (S_4) is shown in Figure 5 and Figure 6 respectively. Time interval from 0[ms] to 200 [ms] shows the electric current changes while both servomotor rotates from 0° to 90°. Both servomotor's current increased to 0.8 – 1.0 [A] before decrease to 0.18 – 0.4[A]. However, there are current noise after 200[ms] which shows that the motor is tried to maintain its angle position. At this point, the torque on the ankle servomotor (S_4) is lower than knee servomotor (S_3) because there are less power required for ankle servomotor (S_4) to maintain the position of the leg.

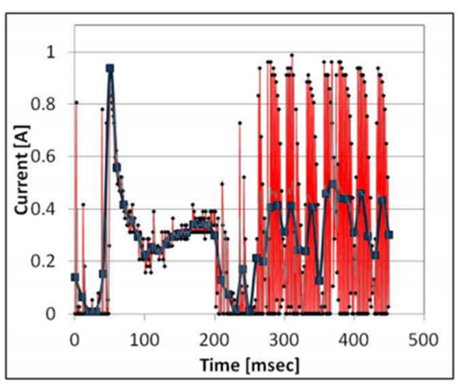


Fig. 5. Knee servomotor (S_3) current

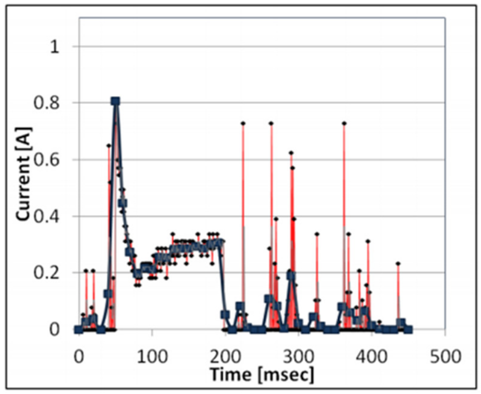


Fig. 6. Ankle servomotor (S_4) electric current

3.2 Optimization of Parallel Linkage Leg

Subsequetly from the result (Figure 5 & 6), one servomotor is allocated to be functioned in each parallel linkage mechanism to determine whether one servomotor is sufficient to support the movement of the leg. Experiments are done by using only knee servomotor (S_3) to rotate from 0° to 90° and the electric current reading is taken. Result in Figure 7 shows similar pattern to the parallel linkage using both servomotor which the current increased to 0.8 – 1.0 [A] before decrease to 0.18 – 0.4[A]. The different is the time taken to achieve desired angle is longer, 250 [ms].

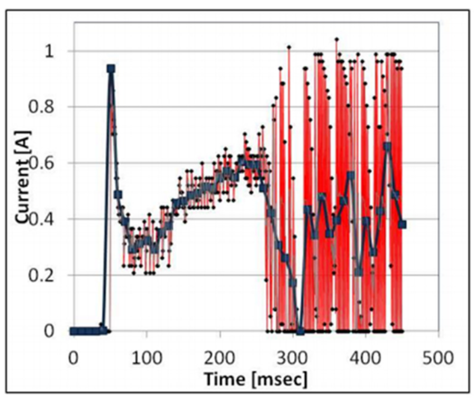


Fig. 7. Knee servomotor current (only S_3)

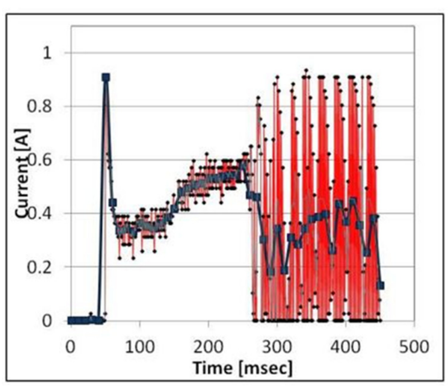


Fig. 8. Knee servomotor current (only S_4)

Next, the same procedure is done using only one ankle servomotor (S_4) and the similar result is achieved when only one knee servomotor is used. (Figure 8). From these, predicted servomotor's torque load is adequate for each parallel linkage mechanism. To inspect the stability, walking gait test for this leg mechanism is implemented.

3.3 Zero-Moment Point (ZMP)

Zero Moment Point (ZMP) method is introduced by MiomirVukobratonic in 1972 to define the stability of the robot when walking and this concept is widely used in Humanoid Robot researches.

ZMP is defined as that point on the ground at which the net moment of the inertial forces and the gravity forces has no component along the horizontal axes [12, 13].

To calculate the ZMP position, assume that the feet do not slide over the floor surface and the floor is rigid and motionless.

ZMP value can be retrieved by attaching force sensor at the foot sole (Figure 9). When 4 sensors are used at each leg, ZMP position when the robot is in initial static condition illustrates in Figure 10 below.

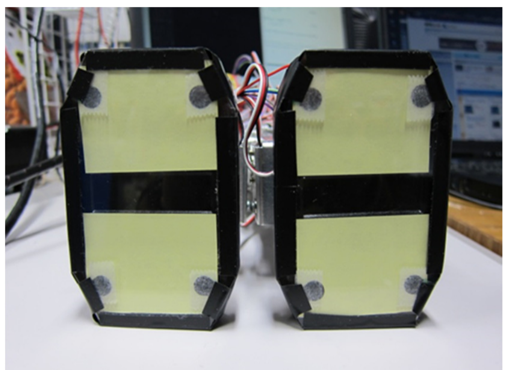


Fig. 9. Pressure Sensor on Foot Sole

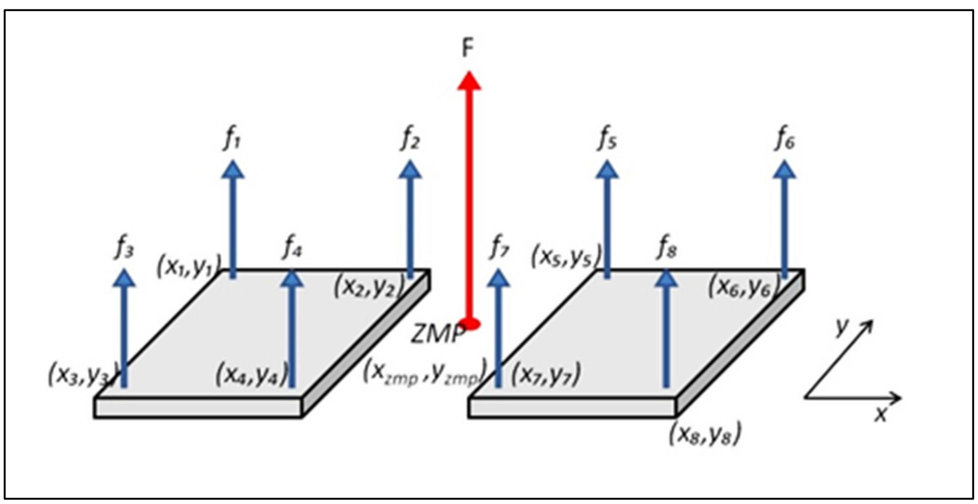


Fig. 10. ZMP Calculation point

When moment around the ZMP is zero, ZMP can be calculated as Eq. (3) and (4) below.

$$x_{zmp} = \frac{\sum_{i=1}^{n} x_i f_i}{\sum_{i=1}^{n} f_i} \tag{3}$$

$$y_{zmp} = \frac{\sum_{i=1}^{n} y_i f_i}{\sum_{i=1}^{n} f_i} \tag{4}$$

where, f_i is applied force on sensor, x_i is sensor position at the x-axis and is sensor position at the y-axis.

3.4 Walking Gaits

The resultant ZMP for Y and X-axis is shown in Figure 11 and Figure 12. The hidden line areas show the support areas of the foot sole and the center line is reference ZMP.

Using ZMP method, robot stability during walking movement can be approved by locating ZMP coordinate. The ZMP value which is near the ZMP's maximum or minimum line indicates that it would fall and lost stability. However, the ZMP value which is smooth and approaching reference ZMP line could be stated as stable in this experiment.

The ZMP values with no control are shown in gray line below. It shows that using parallel-linkage leg structure during walking movement, the robot inclined slightly to the front and the ZMP value becomes larger when the robot is nearly stopping. This is because the proposed parallel-linkage leg's foot sole is always horizontal to the floor surface when robot is walking forward; so that there is a need for a control system.

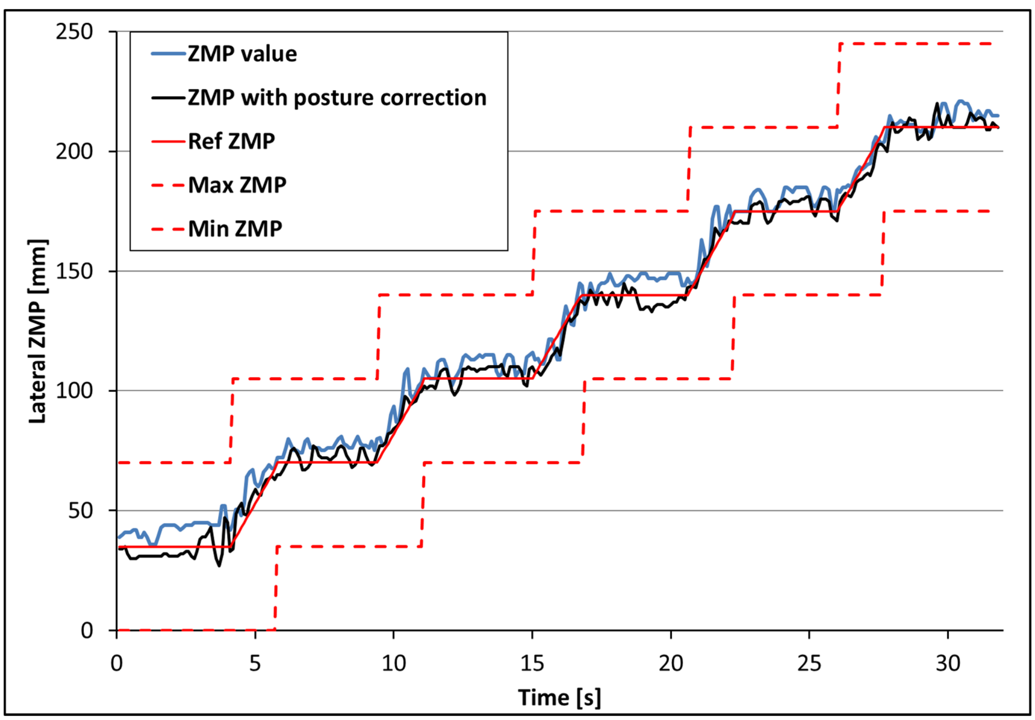


Fig. 11. Y-axis ZMP graph during walking (sagittal plane)

To correct this posture problem that occurred in proposed parallel-linkage leg, gyro sensor is used to measure the angular speed and feedback control is applied to maintain the stability of the robot during walking gaits. This sensor is attached at the back of the body. The resultant ZMP is shown as black line in Figure 10 above. This ZMP line approaches reference ZMP when gyro sensor is used. This posture correction method using gyro sensor proved that even toe is always parallel to the walking surface; stable walking gaits could be achieved.

The same posture correction method is also applied to the X-axis to correct the instability on frontal plane. The resultant ZMP is shown in Figure 12. Even roll axis of the ankle joint do not use the same parallel mechanism as pitch axis, the improvement of body posture control can be seen due to parallel linkage rigidity structure.

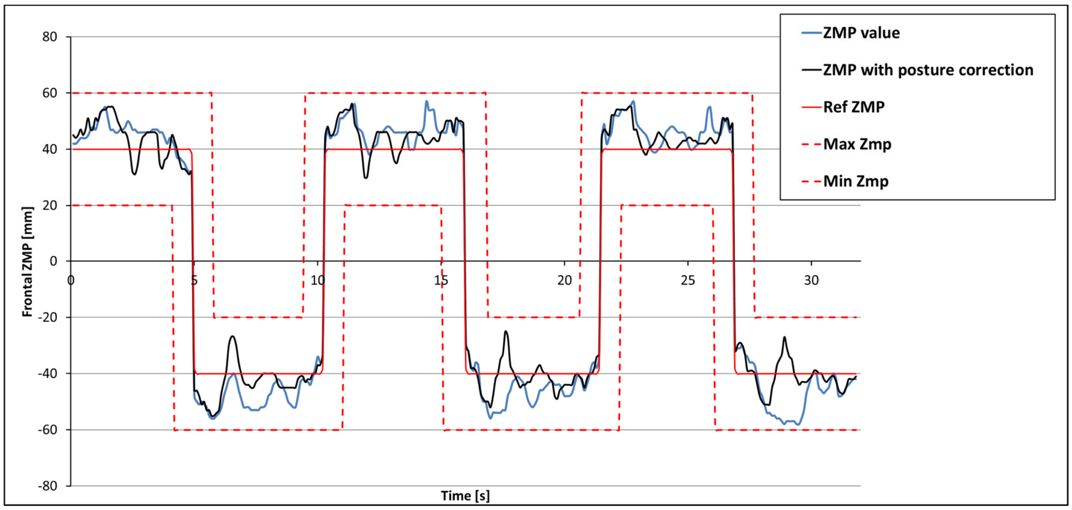


Fig. 12. X-axis ZMP graph during walking

4. Conclusion

In this paper, the proposed parallel-linkage leg structure capable of reducing the high load impact on servomotor by utilizing parallelogram mechanism and concurrently shows improvement in the stability of robot during walking gait trajection. The superiorities of this parallel mechanism are having high rigidity on their structure and lightweight links can be used. Even the toe joint always parallel to the walking surface, body posture can be controlled using gyro sensor feedback.

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