Omni-directional Gait Control of Quadruped Walking Robot

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Abstract: A quadruped walking robot has a superior adaptablility as well as highly adaptable mobility in various environments. These special advantages are outstanding in the mobile robot group. In this work, we introduce the method for omni-directional gait and rotational gait which is the generalized control algorithm to perform any direction commands. In addition, to improve the stability of quadruped walking robot, we performed the optimization between walking angle and sequence of feet. The proposed ideas are applied to the actual design of MRWALLSPECT III(Multifunctional Robot for Wall inSpection version 3) that is designed to inspect of the large surface of industrial utilities. By implementing the proposed idea on the robot, it's effectiveness is experimentally confirmed.

Keywords: MRWALLSPECT, Walking robot, Omni-directional gait

1. Introduction

As the walking robot has more excellent adaptability than others vehicle [1], many people have researched in the gait pattern and the stability of a robot and then developed the robot [2] [3] [4]. In particular, a quadruped walking robot is superior to six leg's robot in respect of control, capacity and efficiency. So, many researchers have studied a quadruped walking robot.

The gait pattern of a quadruped robot is classified into static walking(crawl gait) and dynamic walking(trot gait, pace gait, gallop gait) by a duty factor. In the static walking, it is important that a robot walk stably in a various terrain and move naturally in any direction. Hirose classified various environments of a terrain into five groups. And then, he presented the method to determine the sequence of feet in the terrain and the algorithm that was able to overcome the obstacle in the environment. Also, he presented the method to determine the position of a foothold within the reachable area of a robot [5]. He has began to study various gait patterns of a quadruped robot by presenting the algorithm of circular gait in free radius [6]. Also, he sought a quick mobility by presenting natural gait transition among forward/backward, crab, left/right gait [7]. Including the dynamic factor, Hugel tested for gait transition [8]. Ma explained the algorithm of the more stable omni-directional walking and quick gait transition [9]. In the static walking, the stable walking of a robot is important. Chen, Yoneda, Papadopoulos discussed stability of the static walking [10] [11] [12]. And then, Hirose had compared with various criterions of stability [13].

But, in previous researches, they limited a reachable area to a rectangle for stability of a robot. At the time of foot movement, they don't consider the variation of a COG(Center Of Gravity). Also, because the method of determining the sequence of feet and gait pattern is complex, the robot developed by them is restricted to use in an industrial field.

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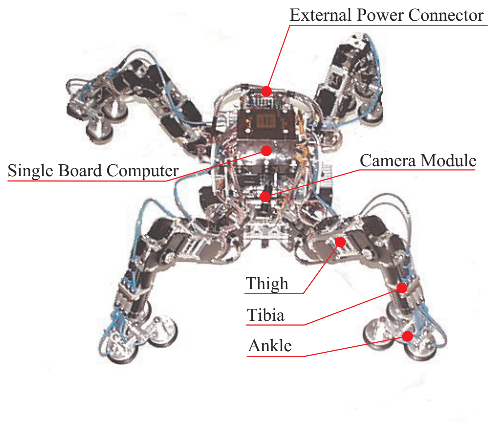

Fig. 1. MRWallspect3

In this thesis, we respectively explained the structure of our robot in chapter one, the algorithm of omni–directional walking in chapter two and the algorithm of rotational walking in chapter three. And than, we presented the result of experiment and discussed it. At last, we concluded in chapter five.

2. MRWALLSPECT III

2.1. Mechanism

As shown in fig 1, our robot consisted of a body and four legs with three DOF(degrees of freedom). With the purpose of stable walking in a steep slope and a vertical wall environment, we made the body as a trapezoid shape that the interval between front legs is narrow and the one between rear legs is wide. And, the sole of feet is attached suction pads. To move free in supporting mode whether the body move in any direction, the robot ankle consisted of spherical joint. Also, by applying to the concept of *manipulability*, we designed the length of thigh and tibia to equal in robot legs [14].

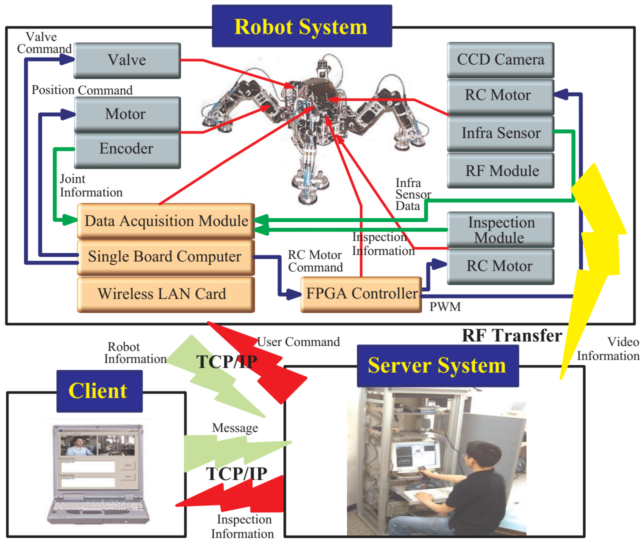

Fig. 2. The whole robot system

The analysis of kinematic and inverse kinematic solution is equal with manipulator of three DOF(Degrees Of Freedom) in the robot. So, we solved the kinematic and inverse kinematic solution of the robot like that and applied to four legs equally.

2.2. The whole System

The whole system of our robot is shown in the fig 2. The whole system is classified into three groups that had the robot system, server system and client system. Also, each system held all information in common through the wireless communication.

We have two controllers in the robot system. The one is a embedded controller by RTLinux, and another is a FPGA controller which controlled RC servo motor. The robot system controlled all motor and CCD Camera module as the user's command. The CCD Camera module consisted of RC servo motor with two DOF and CCD Camera. And, the module sent the video information to server system by RF(Radio Frequency) sender.

The server system showed the present posture of the robot by using the information that is sent from robot system. And than, it sent the user's command to robot system. Also, the server system allow the other client to connect and send the information of the robot. The client is able to get all information of the robot.

3. Omni–directional walking

3.1. Gait pattern control

The many researchers has studied at a quadruped walking robot. The reachable area of legs used by them is a rectangular shape and a symmetrical structure in the direction of left/right and forward/backward. This structure restricted the mobility in the direction of the walking angle and had a complexity in respect of gait control of omni-directional and rotational walking. So, in this study, we defined the reachable area as a fan shape and tried to control the robot by using it.

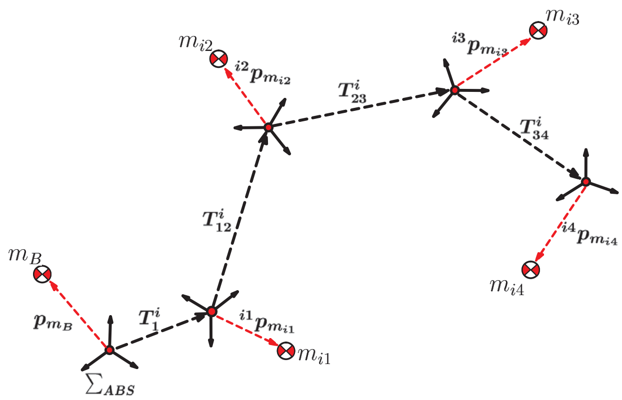

Fig. 3. Mass distribution

As the robot is walking, it is necessary that we control the COG of the robot stably. So, we must calculate the positon of the COG in the robot. In this study, as shown in fig 3, we divided the robot into five groups that is the body, hip, thigh, tibia and ankle. And, we defined the mass of each part as m_B, $m_{i1}, m_{i2}, m_{i3}, m_{i4}$ and the position of COG as $\mathbf{p}_{mB}, {}^{i1}\mathbf{p}_{mi1}, {}^{i2}\mathbf{p}_{mi2}, {}^{i3}\mathbf{p}_{mi3}, {}^{i3}\mathbf{p}_{mi4}$ respectively. Also, we defined the COG position of robot as the vector, $\mathbf{p}_{CG} = [c_x \quad c_y \quad c_z]^T$. And then, we calculate moment equilibrium equation in the standard coordinate system, $\sum_{ABS}$. that can be described as

$$\mathbf{p}_{CG} \times m_T \hat{\mathbf{g}} = \sum_{i=1}^{4} \sum_{j=1}^{4} \mathbf{p}_{mij} \times m_{ij} \hat{\mathbf{g}} + \mathbf{p}_{mB} \times m_B \hat{\mathbf{g}} \qquad (1)$$

Where, i and j is the number of leg and joint respectively. And, m_T is the total weight of the robot.

If we define $\hat{\mathbf{g}} \triangleq [\mathbf{g_1}, \mathbf{g_2}, \mathbf{g_3}]^{\mathbf{T}}$, skew-symmetric matrix is as follows.

$$\hat{\mathbf{g}}_{\mathbf{s}} \triangleq \begin{bmatrix} 0 & -g_3 & g_2 \\ g_3 & 0 & -g_1 \\ -g_2 & g_1 & 0 \end{bmatrix} \qquad (2)$$

Therefore, by using the equation 3 as follows, we can calculate the position of the COG in the robot.

$$m_T \hat{\mathbf{g}}_s \mathbf{p}_{CG} = \sum_{i=1}^{4} \sum_{j=1}^{4} m_{ij} \hat{\mathbf{g}}_s \mathbf{p}_{mij} + m_B \hat{\mathbf{g}}_s \mathbf{p}_{mB} \qquad (3)$$

In the static walking, if virtual center of gravity(abbreviated VCG, in this paper) denotes the point that the position of COG is projected into the ground, to walk stably, VCG must be within the triangle that is made by supporting feet. So, before swinging the foot, the VCG is moved within the triangle and the trajectory of the movement is vertical to a diagonal line for the purpose of minimizing the distance of the movement. For example, as shown in fig 4, before the leg3 move, VCG must go to the position of VCG$'$.

3.2. Determine the foot tracjectory

The state of the leg is divided into supporting and swinging mode in walking robot. If we keep walking angle, α, constant in the swinging mode and the trajectory of the leg always pass through common position, $C_i(x_{ci}, y_{ci}, z_{ci})$, as

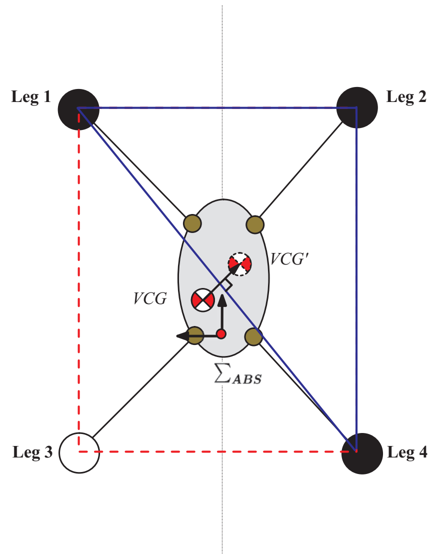

Fig. 4. Movement of VCG

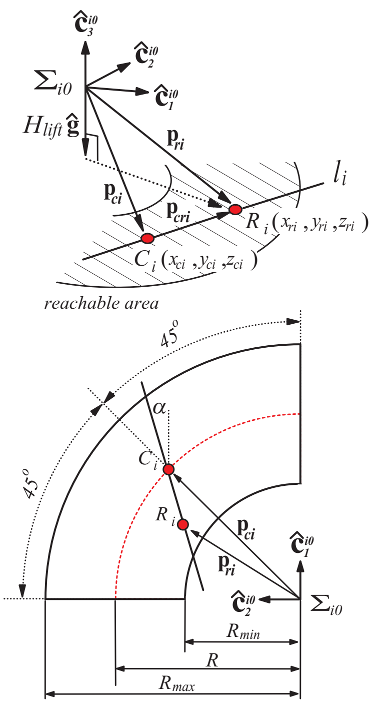

Fig. 5. Reachable area

shown in fig 5, ${}^{i0}\mathbf{p}_{ri}$ is described as the equation 4 by using the parameter, t_{pi}, that denoted the stroke of each leg.

$$ {}^{i0}\mathbf{p}_{ri} = [x_{ci} + t_{pi}\cos\alpha \quad y_{ci} + t_{pi}\sin\alpha \quad -z_{ci}]^T \tag{4}$$

In the equation 4, we can describe ${}^{ij}\mathbf{p}_{ri}$ as the parameter equation of the space in the standard coordinate system, $\sum_{ABS}$, and is shown as

$$\mathbf{p}_{ri} = \mathbf{T}^i_j \ {}^{ij}\mathbf{p}_{ri} \tag{5}$$

Where, $\mathbf{T}^i_j$ denotes homogeneous matrix in the standard coordinate system(i : leg, j : joint). To determine the trajectory of feet, we calculate the stroke of each leg, t_{pi}, to satisfy the condition of the equation 6.

$$|{}^{ij}\mathbf{p}_{ri}| = \sqrt{{R_{max}}^2 + {H_{lift}}^2} \tag{6}$$

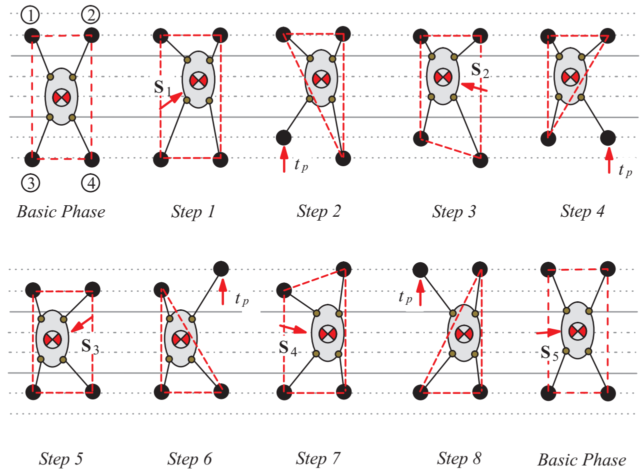

Fig. 6. Gait pattern of the static walking

Table 1. The sequence of feet and range of walking angle to minimize S

Range of walking angle	Sequence of feet
$0 \sim 6$	3,2,0,1
$6 \sim 40$	2,3,0,1
$40 \sim 59$	3,1,0,2
$59 \sim 68$	1,3,0,2
$68 \sim 93$	1,0,3,2
$93 \sim 221$	1,3,0,2
$221 \sim 231$	0,1,2,3
$231 \sim 356$	2,3,0,1
$356 \sim 360$	3,2,0,1

Where, R_{max} and H_{lift} is the outside radius of reachable area and the height of the standard coordinate system from the ground respectively. And then, we choose the minimum thing of the results in case of $i = 0, 1, 2, 3$, and use by the stroke of the robot . Also, with using the stroke of the robot, we are able to get the vector,${}^{i0}\mathbf{p}_{cri}$,to show the trajectory of the swinging foot and is shown as

$$ {}^{i0}\mathbf{p}_{cri} = {}^{i0}\mathbf{p}_{ri} - {}^{i0}\mathbf{p}_{ci} \tag{7}$$

Therefore, from the equation 7, the foot of the robot passed through the trajectory, ${}^{i0}\mathbf{p}_{cri}$.

3.3. Determine the sequence of feet

As shown in fig 6, we define the movement distance of the COG for a cycle as $S_i (i = 1, 2, 3, 4, 5)$ and the maximum distance among the values as S. that is shown as

$$S = max(S_1, S_2, S_3, S_4, S_5) \tag{8}$$

The smaller the value of S, the shorter the movement distance of VCG. Hence, the robot is able to walk stably and fast. Therefore, we determined the sequence of feet to minimize the value of S in all cases of foot step(twenty fore cases). As shown in fig 7, we showed the relations between S and walking angle. From the fig 7, we listed the sequence of feet as table 1.

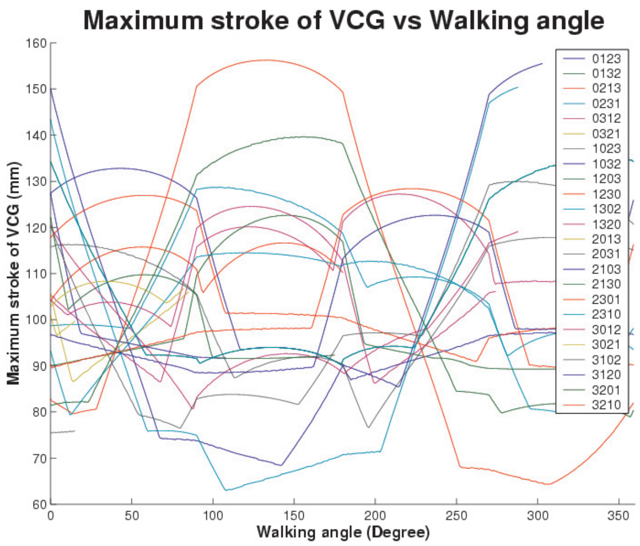

Fig. 7. Determining the sequence of feet

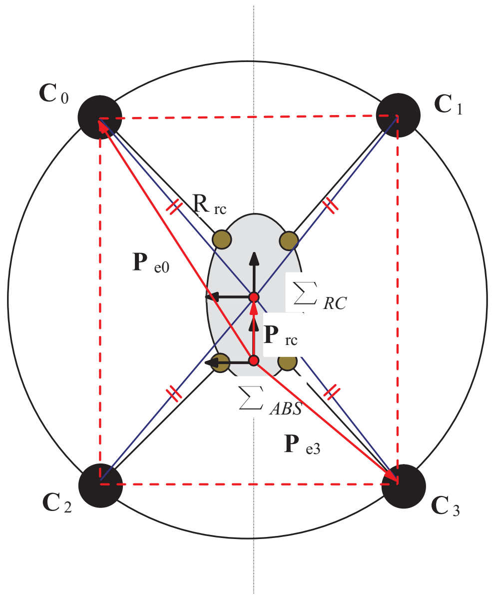

Fig. 8. The trajectory of feet in the rotational walking

Therefore, when an user change the walking angle of the robot, the robot change the sequence of feet in accordance with the table 1.

4. Rotation walking

In case of doing the specific working, the robot must be able to rotate for better mobility in direction of clockwise and counter clockwise at the standing place. To change just the direction of the robot in the rotational walking, we generate the trajectory of circle which passed through the common position of the four feet and let the robot rotate along the trajectory. As shown in fig 8, we can get the center position of the circle, $\mathbf{p}_{rc}$, and radius, R_{rc}, from the equation 9 and the equation 10.

$$|\mathbf{p}_{rc}| = \frac{|\mathbf{p}_{e0}|^2 - |\mathbf{p}_{e3}|^2}{2(p_{e0_x} - p_{e3_x})} \tag{9}$$

$$R_{rc} = |\mathbf{p}_{e0} - \mathbf{p}_{rc}| \tag{10}$$

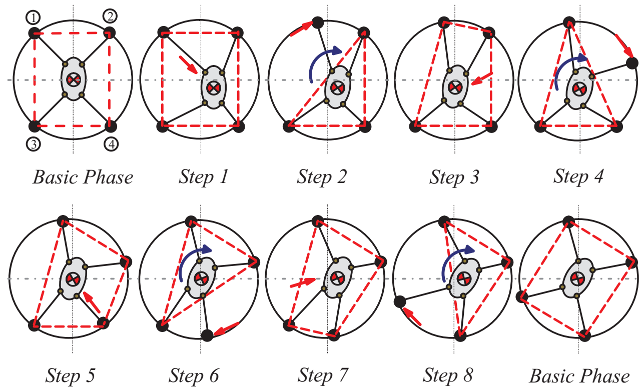

Fig. 9. Gait pattern of the rotational walking

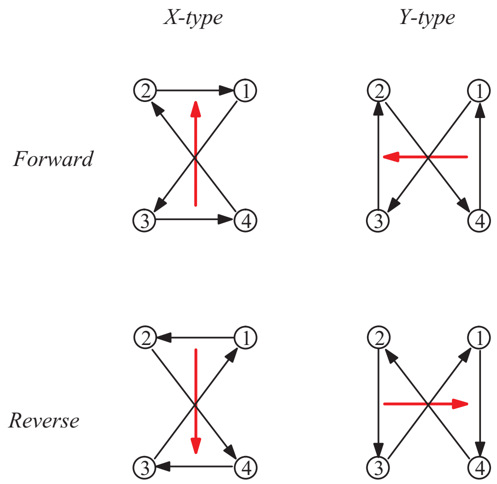

Fig. 10. The standard gait

Where, $\mathbf{p}_{e0}$ and $\mathbf{p}_{e3}$ is the vector from the standard coordinate system to C_0 and C_3. From above equations, we are able to get the trajectory of feet and accomplish the rotational walking. The process of rotational walking is shown in fig 9. If the robot rotate at an angle of 20 degree, the swinging leg rotate at all angle(20 °) and the robot body rotate at one over four of all angle in step 2, step 4, step 6 and step 8 respectively.

5. Experiments and Discussion

First of all, we prove that the foot sequence of the table 1 is superior to the standard gait in our robot. The standard gait is used by many researchers [6] [9] [15] and the gait pattern is shown in fig 10. We compare the maximum stroke versus walking angle in the our result with the one in the standard gait. This result is shown as follows From the fig 11, we know that our result have better mobility than the standard gait in our robot.

As shown in fig 12, we tested the presented algorithm in the simulated environment. And than, we applied the algorithm to MRWALLSPECT III. The specification of MRWALLSPECT III is shown in table 2.

First, as shown in fig 13, we experimented the omnidirectional walking. The user commanded the robot to go forward, right(crab walking) and in direction of 135 ° through wireless communication in sequence.

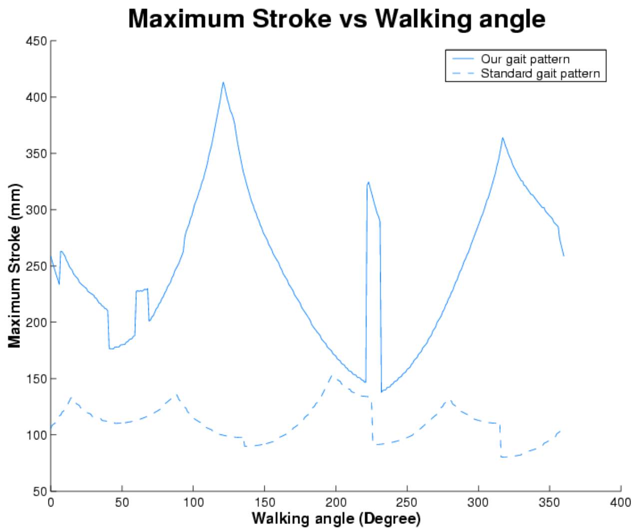

Fig. 11. The maximum stroke versus walking angle

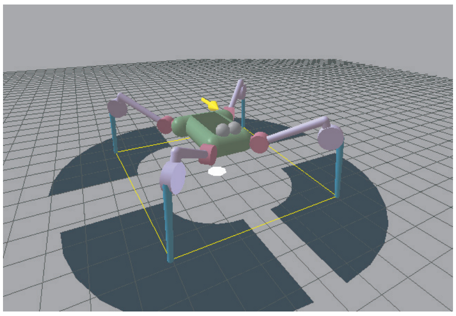

Fig. 12. The simulation program

Table 2. The robot specification

Item	Content
Number of leg	4 EA
Maximum speed	50 cm/min
Maximum stroke	200 mm
Weight	35 kgf
Payload	10 kgf
Length	1.3 m(Included length of leg)
Degrees of Freedom	3 DOF/Leg

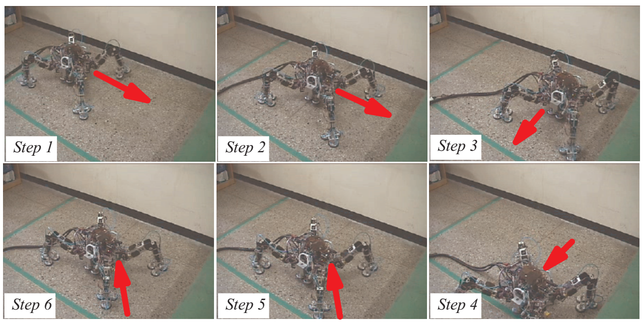

Fig. 13. Experiment of omni-directional gait

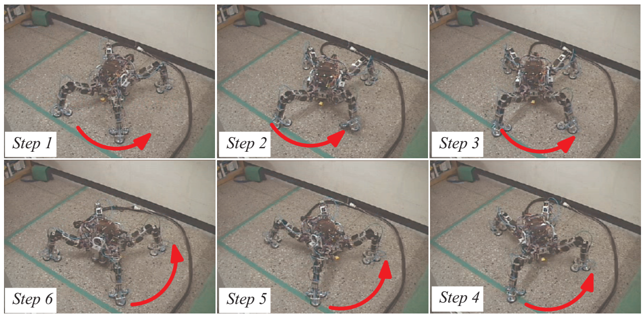

Fig. 14. Experiment of rotation gait

Second, as shown in fig 14, in purpose of experiment the rotational walking, the user commanded the robot to rotate in direction of clockwise.

6. Conclusion

In this study, we present the control method of the robot for the stable walking of quadruped robot and the algorithm of omni-directional walking and rotational walking for the superior ability. Also, we performed the optimization between the walking angle and the sequence of feet for our robot. And than, we applied the algorithm and the sequence of feet to the constructed robot, MRWALLSPECT III. The robot executed the omni-directional and rotational walking successfully just as user commands without an unstable state. In our future study, we will discuss more various gait pattern.

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