Steering Control Algorithm of a Locomotion Robot Using a Quaternion with Spherical Cubic Interpolation (ICCAS 2005)

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Abstract: This paper presents the steering control algorithm of a locomotion robot using a quaternion. The locomotion robot is to be moved on an irregular floor that can inevitably result in the errors of both position and orientation. Especially the orientation error should be compensated every work in order to adjust the misaligned values of current orientation to those commanded values. In this paper, we propose a new steering control algorithm between the two values by using a quaternion with spherical cubic interpolation. The proposed algorithm is shown to be effective in terms of vibration when compared to a conventional simple compensation without interpolation, by using MATLAB® and VisualNastran4D® .

Keywords: Steering Control, Lcomotion Robot, Position and Orientation, Quaternion, Spherical Cubic Interpolation

1. INTRODUCTION

The locomotion robot is to be moved on an irregular floor that can inevitably result in the errors of both position and orientation. The mass center of the robot is located at the upside of robot as shown in Fig 1. This means that a slight error in position and orientation at starting stage can be enlarged at final stage. Especially the orientation error should be compensated every work in order to adjust the misaligned values of current orientation (measured by 8 ultrasonic sensors). A conventional simple compensation has no interpolation between the two values, which can result in motion with large vibration and in turn let the robot fall down. In this paper, we propose a new steering control of compensation for the errors, by using a quaternion with spherical cubic interpolation. This proposed control using a quaternion with spherical cubic interpolation aims at generating the smooth steering of a locomotion robot of which payload is heavy with about 250 kg_f and the mass center is located at its upside. In specific, without such smooth steering, the robot could be fallen down due to an unstable configuration in the rapid change of orientation.

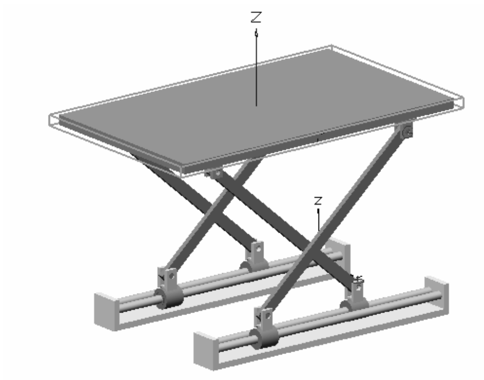


Fig. 1 Locomotion Robot

Several papers [1-3] on mobile robots have focused on trajectory tracking by using the velocity control of wheels, based on special kinematic definition rather than Denavit-Hartenberg notation [4]. Muir et al. [1] has applied different kinematic approach to a robot body and its wheels separately, by using Sheth-Uicker notation. Shin et al. [2] have proposed the kinematic model of 2-DOF(Degree Of Freedom) 3-wheeled robot. Chung et al. [3] has contributed to the trajectory control of a 2-wheeled simultaneously-driven robot. Therefore up-to-date researches on a mobile robot have a trend in its steering within long range. Moreover, each front wheel of the locomotion robot with four wheels has an additional steering servomotor as well as a rotation servomotor, because the robot is heavy with about 250kg_f for installing a arc welding robot. The robot has total 3-DOF because two steering servomotors are constrained in one degree of freedom. Without steering servomotors, the heavy weight of robot would have difficulty in getting steering control over the two front wheels by using the velocity differentials between two front wheels.

In this paper, the motion control of the locomotion robot has on fine steering within short control range such as floor in the factory. This means that the up-to-date researches on mobile robot cannot be directly applied to the motion control of the locomotion. At first, this paper presents an analytical approach to the smooth and fine steering control of locomotion robot by using a quaternion with spherical cubic interpolation. Then the effectiveness of proposed steering algorithm will be verified in terms of vibration by the simulation using the dynamic modeling software, VisualNastran4D®, compared to the conventional simple steering without interpolation.

2. COORDINATE SYSTEM

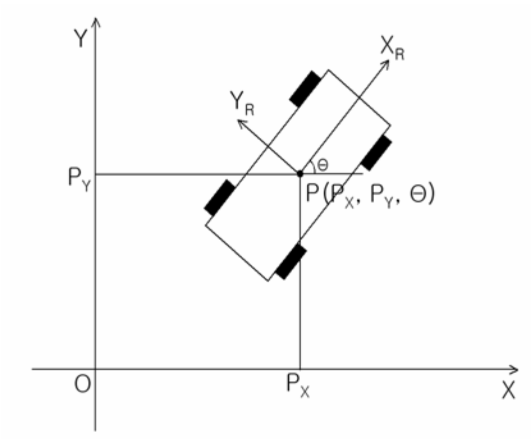


Fig. 2 Coordinate System

Figure 2 shows the coordinate system of the locomotion robot whose position P can be defined by using three variables such as P_x, P_y and θ in the world coordinate system. The position point P in the world coordinate system is given by Eq. (1) :

$$P = (Px, Py, \theta)^{T} \quad (1)$$

In addition, the rotation matrix which denotes the orientation of the locomotion robot is given by Eq. (2) :

$$R(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

3. PROBOLEM STATEMENT

As shown in Fig. 3, the moving part of the locomotion robot consists of four wheels. Especially each front wheel has two servomotors for one positioning servomotor (ω_i, $i = 1,2$) and another steering servomotor (Ω) as shown in Fig. 3. But the total DOF of the robot is 3, *i.e.,* two rotations (ω_1 and ω_2) and one steering (Ω) because the two steering servomotors are constrained in one swivel.

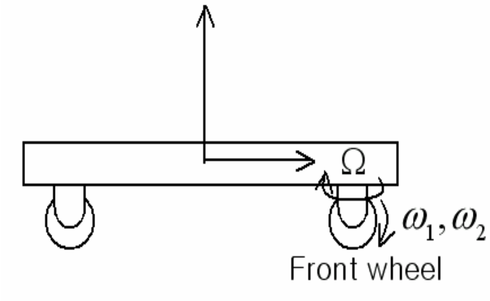


Fig. 3 Moving Part

The coordinates by which the locomotion robot is controlled are the front wheel steering angle Ω and drive velocity ω.

3.1 Simple Steering angle

Figurer 4 shows the trajectory of the locomotion robot if it turns 90°. And the simple steering angle is shown in Fig. 5 where the acceleration and deceleration of a steering AC servomotor is neglected.

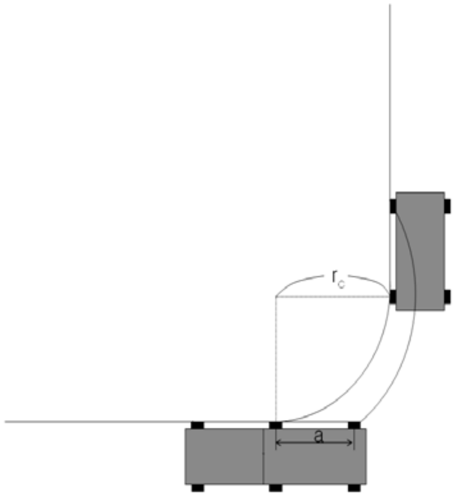
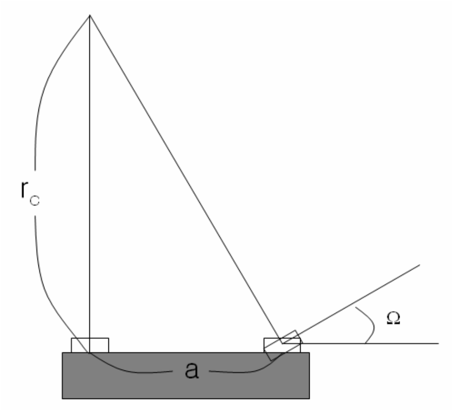
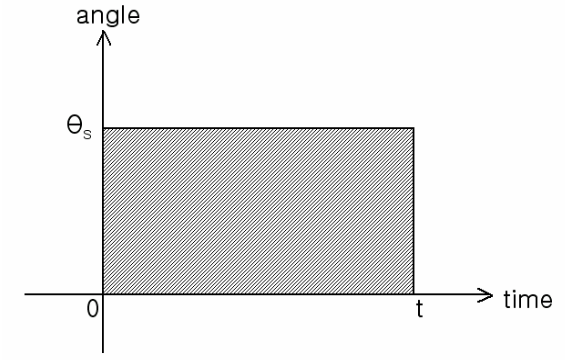


Fig. 4 The Simple Steering Trajectory of the Locomotion Robot



(a)



(b)

Fig. 5 (a) Steering Angle of the Locomotion Robot
(b) Simple Steering Angle

The Simple Steering Angle θ_s is given by Eq.(3) :

$$\theta_s = \Omega = \tan^{-1}(\frac{a}{r_c}) \tag{3}$$

For real implementation of acceleration/deceleration on a steering servomotor, fine steering should be found for the stable locomotion of the robot. This point is the motivation of our paper.

3.2 Smooth Steering Angle

Figure 6 illustrates that the trajectory of robot can be defined by using both the first position $P_1(P_{x1}, P_{y1}, \theta_1)$ and the next position $P_2(P_{x2}, P_{y2}, \theta_2)$. Of course, P_1 and P_2 can be given by OLP. First of all, the position of point A can be found by crossing the two lines $\overline{P_1A}$ and $\overline{AP_2}$. Then we make another point $P_2'(P_{x2}', P_{y2}', \theta_2)$ by letting $\overline{P_1A}$ equal to $\overline{AP_2'}$. The remained path $\overline{P_1P_2'}$ can be tracked without any steering. The angle between $\overline{P_1A}$ and $\overline{AP_2'}$ can be obtained by Eq. (4) :

$$\angle P_1AP_2' = \pi - (\theta_2 - \theta_1) \tag{4}$$

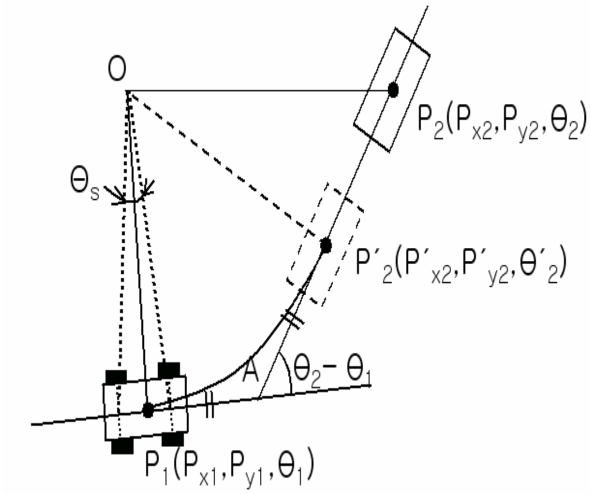


Fig. 6 Trajectory of Locomotion Robot

Second, the angle of rotation $\angle P_1OP_2'$ and the radius of curvature $\overline{OP_1}$ can be found by Eqs. (5) and (6), respectively :

$$\angle P_1OP_2' = \theta_2 - \theta_1 \tag{5}$$

$$\overline{OP_1} = \frac{\overline{P_1A}}{\tan\frac{\theta_2 - \theta_1}{2}} = \frac{\overline{P_2'A}}{\tan\frac{\theta_2 - \theta_1}{2}} \tag{6}$$

The length of trajectory S can be given by Eq. (7) :

$$S = \overline{OP_1} \times \frac{(\theta_2 - \theta_1)}{360°} \tag{7}$$

The velocity of the locomotion robot, v, is usually given. Then the steering time (t) and the angular velocity of wheel (ω) can be found by Eqs. (8) and (9), respectively :

$$t = \frac{S}{v} \tag{8}$$

$$\omega = \frac{v}{r} \tag{9}$$

Following the first and second steps can make the path of robot's position track the planed trajectory. However, the fine steering control for the orientation of locomotion robot still remains to be solved when the angle of rotation θ_s (see Fig. 5) is given. A good candidate scheme for this smooth steering is to interpolate the angle of rotation by using a quaternion with spherical cubic interpolation. The interpolation using a quaternion will be performed only for the range from a starting zone of a curved path to the mid-point of the curvature, *i.e.*, the steering angle $\dfrac{\theta_2-\theta_1}{2}$, while the remained half part from the mid-point to an ending zone of the curved path is made symmetrical considering the outgoing part of the curved path.

4. INTERPOLATION

In general, Euler angle notation [4] is widely used for orientation, but it has some bottleneck in making interpolation between rotation matrices. A quaternion has been introduced for the notation of orientation since it has simple notation of rotation as well as being convenient for the interpolation for orientation. The quaternion can express itself into a rotational axis and rotational angle about the axis. The quaternion can be defined by Eq. (10) :

$$\mathbf{q}=w+(x\mathbf{i}+y\mathbf{j}+z\mathbf{k}) \tag{10}$$

Here x, y, z, w are real numbers while $x\boldsymbol{i}, y\boldsymbol{j}, z\boldsymbol{k}$ denote complex numbers. Due to the characteristics of complex numbers, it follows that

$$\boldsymbol{i}^2=\boldsymbol{j}^2=\boldsymbol{k}^2=-1,$$
$$\mathbf{ij}=\mathbf{k},\mathbf{jk}=\mathbf{i},\mathbf{ki}=\mathbf{j},\mathbf{ijk}=-1$$

Here it can be said that x, y and z denote the axis of rotation while w indicates the angle of rotation. Addition and subtraction of quaternion is defined by Ea. (11) :

$$\begin{aligned}&\mathbf{q}_0\pm\mathbf{q}_1\\&=(w_0+x_0\mathbf{i}+y_0\mathbf{j}+z_0\mathbf{k})\pm(w_1+x_1\mathbf{i}+y_1\mathbf{j}+z_1\mathbf{k})\\&=(w_0\pm w_1)+(x_0\pm x_1)\mathbf{i}+(y_0\pm y_1)\mathbf{j}+(z_0\pm z_1)\mathbf{k}\end{aligned} \tag{11}$$

And the dot product of two quaternions is given by Eq. (12):

$$\mathbf{q}_0\bullet\mathbf{q}_1=w_0w_1+x_0x_1+y_0y_1+z_0z_1 \tag{12}$$

Besides, any rotation matrix can be converted into a quaternion as follows [5] :

$$\begin{bmatrix}n_x & s_x & a_x\\ n_y & s_y & a_y\\ n_z & s_z & a_z\end{bmatrix}=\begin{bmatrix}1-2y^2-2z^2 & 2xy-2wz & 2xz+2wy\\ 2xy+2wz & 1-2x^2-2z^2 & 2yz-2wx\\ 2xz-2wy & 2yz+2wx & 1-2x^2-2y^2\end{bmatrix}$$

$$=\mathbf{q}(w,(x,y,z)) \tag{13}$$

Here

$$w=\frac{\sqrt{n_x+o_y+a_z+1}}{2},$$

$$x=\frac{s_z-a_y}{4w},\ y=\frac{a_x-n_z}{4w},\ z=\frac{n_y-s_x}{4w}$$

The rotation matrix denoting the orientation of a locomotion robot is given by Eq. (2). This matrix can be converted into the quaternion $\boldsymbol{q}$ as follows.

$$\boldsymbol{q}=\frac{\sqrt{2\cos\theta+2}}{2}+\frac{\sin\theta}{\sqrt{2\cos\theta+2}}\boldsymbol{k} \tag{14}$$

When both the quaternion corresponding to a starting orientation, $\boldsymbol{q}_s$, and the quaternion corresponding to an mid-point orientation, $\boldsymbol{q}_e$, a steering angle can be obtained by using spherical cubic interpolation. In particular, the concept of spherical cubic interpolation can be delineated in Fig. 7. The spherical cubic interpolation of quaternions can be achieve using a method described in which has the flavor of bilinear interpolation on a quadrilateral.

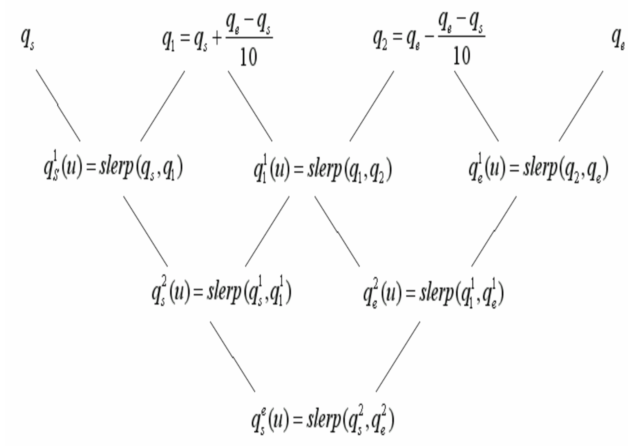


Fig. 7 Spherical Cubic Interpolation

Here, $\mathrm{slerp}(\boldsymbol{q}_1,\boldsymbol{q}_2)$, which can be given by Eq. (15), indicates the spherical linear interpolation.

$$\mathrm{slerp}(\boldsymbol{q}_1,\boldsymbol{q}_2)=\frac{\sin((1-u)\Omega)}{\sin\Omega}\boldsymbol{q}_1+\frac{\sin(u\Omega)}{\sin\Omega}\boldsymbol{q}_2 \tag{15}$$

Here u ($0\le u\le 1$) is a normalized parameter based on time.

Equation (15) can result in the spherical cubic interpolation between $\boldsymbol{q}_s$ and $\boldsymbol{q}_e$ as follows.

$$\begin{aligned}\boldsymbol{q}_s^e(u)&=slerp(\boldsymbol{q}_s^2,\boldsymbol{q}_e^2)\\&=\frac{\sin((1-u)\Omega}{\sin\Omega}\boldsymbol{q}_s^2+\frac{\sin(u\Omega)}{\sin\Omega}\boldsymbol{q}_e^2\end{aligned} \tag{16}$$

In Eq. (16), the steering angle, Ω, between the starting and ending orientations can be obtained by the inner product of two quaternions, $\boldsymbol{q}_s^2$ and $\boldsymbol{q}_e^2$, as follows.

$$\Omega=\cos^{-1}(\boldsymbol{q}_s^2\cdot\boldsymbol{q}_e^2) \tag{17}$$

Thus Eq. (16) can produce an intermediate steering angle according to u .

5. SIMULATION

As shown in Fig. 8, the simulation results of steering angles for the initial condition ($\theta_1 = 0°$) and the final condition ($\theta_2 = 90°$) are shown by using Eq. (16) through MATLAB® . For the trajectory planned by OLP, a locomotion robot can be simulated by using on VisualNastran4D®. As shown in Fig. 9, the panoramic view of steering control illustrates the effectiveness of the proposed steering control algorithm.

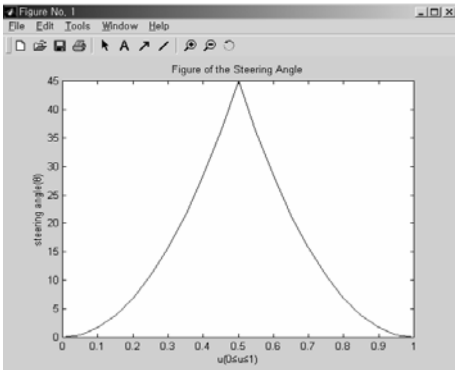


Fig. 8 Steering Angle

Fig. 9 Panoramic View of Steering Control

In order to show the effectiveness of proposed steering control algorithm, we have compared the intermediate steering angle given by Eq. (16), with the simple steering angle shown in Fig. 5, in terms of vibration displacements. This can be noticed in Fig. 10 and 11 corresponding to the proposed steering control and the simple steering control, respectively. Accordingly, the comparison of the proposed steering control with the simple steering control is summarized in terms of the rms (root mean square) and the peak values of vibration displacements. Table 1. This table shows that the proposed steering control can reduce both the rms values and the peak values of vibration.

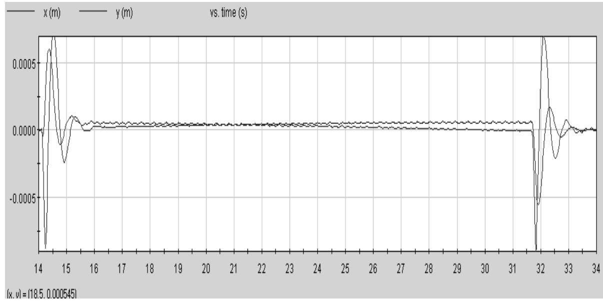


Fig. 10 Vibration Displacement of Simple Steering Control

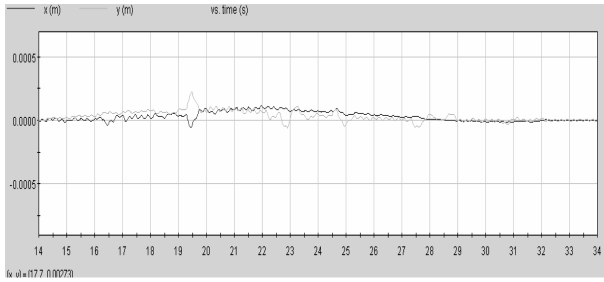


Fig. 11 Vibration Displacement of Proposed Steering Control

Table 1. Comparison of Proposed Steering Control with Simple Steering Control

	Simple Steering Control	Proposed Steering Control
rms (Displacement)	0.0915 ㎜	0.0539 ㎜ (41.4% reduced)
Peak (Displacement)	0.9870 ㎜	0.225 ㎜ (72.2% reduced)

6. CONCLUSION

This paper has proposed the steering control algorithm of a locomotion robot using a quaternion. The locomotion robot is to be moved on an irregular floor that can inevitably result in the errors of both position and orientation. The error should be compensated every work in order to adjust the misaligned values of current position and orientation (measured by 8 ultrasonic sensors). A conventional simple steering control has no interpolation between the two values, which can result in motion with large vibration and in turn let the robot fall down. In this paper, we proposed a new steering control of compensation for the errors, by using a quaternion with spherical cubic interpolation. This proposed control using a quaternion with spherical cubic interpolation has generated the smooth steering of a locomotion robot of which payload is heavy with about 250kg_f and mass center is located at its upside. The proposed algorithm has shown to be effective in terms of vibration when compared to a conventional simple steering control without interpolation, by using MATLAB® and VisualNastran4D®.

ACKNOWLEDGMENTS

This work was supported in part by the Korea Science and Engineering Foundation (KOSEF) through the Machine Tool Research Center at Changwon National University and Robot Valley Co., Ltd. This work was also supported in part by Knowledge-based Mechanical parts and Materials R&D Cluster (K-MEM R&D Cluster) at Changwon National University. This work was also supported in part by the Ministry of Commerce, Industry and Energy (MCIE) through the program for cultivating graduate students in regional strategic industry. This research is financially supported by Changwon National University in 2004.

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