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Kinematic analysis and positioning performance evaluation of a structurally stability-enhanced ballbot

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Abstract

Ballbots are advanced mobile robots which actively balance on a single spherical ball, and has the benefits of (a) omni-directionality (b) single contact point with the ground and (c) dynamic stability. Ballbot models which have been previously developed used an inverted mouse-ball drive and a three omni-wheel system to transmit power to the ball. The earliest design used four rollers located at the lower half of the ball while the later designs used omni-wheels located at the upper half of the ball to drive the ballbot. In this paper, a novel design of ballbot is suggested. In the proposed model, the omni-wheels are relocated to the bottom half of the ball, reducing the overall height of the mobile robot. The ball of the ballbot makes contact with other elements at five points out of which three points are used for actuation. In the ballbot, the rotational movement of the omni-wheels was transformed into planar movement. The velocity kinematics of the robot was derived using differential motion transformation. The positioning performance of the ballbot was evaluated using a coordinate measuring machine and reference ball setup and the positioning error was determined.

Keywords: robot, ball, kinematic, analysis

1. Introduction

Robots are increasingly being enabled with the ability of human interaction. Mobile robots would particularly benefit from this addition. Omnidirectional movement of the mobile robot is an important human-like characteristic which makes human-robot interaction more natural. Ballbots, which are robots that actively balance on a single spherical wheel [1], come very close in replicating a human being's omnidirectionality. Ballbots can be used as personal assistants particularly in homes and hospitals when human help is unavailable. Lauwers et al. introduced the first ballbot known simply as the Ballbot [2] which used an inverse mouse-wheel mechanism for actuation of the ball. Later, Kumagai and Ochiai introduced the BallIP [3] which used three omni-wheels towards the top of the ball for ball actuation. These ballbots are truly exceptional mobile robots because these robots actively compensate the shift in the robot's center of gravity by pure control of the actuating mechanism. The kinematic and dynamic relationship between the actuating mechanism and the ball are important for the role of locomotion as well as balancing. This paper presents a novel design of a ballbot that is different from previous ballbots. The omni-wheels used for actuation, are shifted towards the bottom of the ball. The kinematics of the ballbot are studied, its positioning performance is evaluated and the positioning error is determined.

2. Structural Configuration of the ball based mobile robot

The current design of the proposed ballbot uses a ball which is held in place by using a central circular fixture, which supports the weight of the mobile robot. Three motors are secured to the upper plate and drive the ball through three omniwheels and its corresponding shafts. The ball contacts the

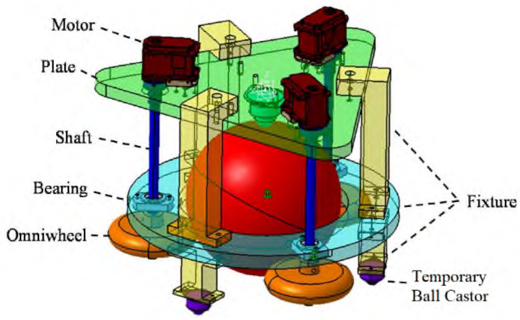

Figure 1. Three dimensional model of the ballbot

floor as well as three omniwheels and a ball castor on the top of the ball, thereby making five points of contact. The ballbot model currently uses three temporary ball castors instead of a control mechanism to keep the structure in balance and it is planned to be removed after balancing control is added. The three dimensional model of the proposed robot is shown in Figure 1.

3. Kinematic relationship between ball and omniwheels

The kinematic relationship between the ball and the omniwheels can be found by the principle of differential motion transformation. In the mobile robot, the omniwheels are the driving mechanism and the ball is the driven part. In the analysis that follows, the velocity of the omniwheel is calculated based on the velocity of the ball in a specified direction.

3.1. Differential motion transformation of omniwheel with respect to the ball

The transformation of the omniwheel coordinate system {*M*} with respect to the ball coordinate system {*F*} can be derived by

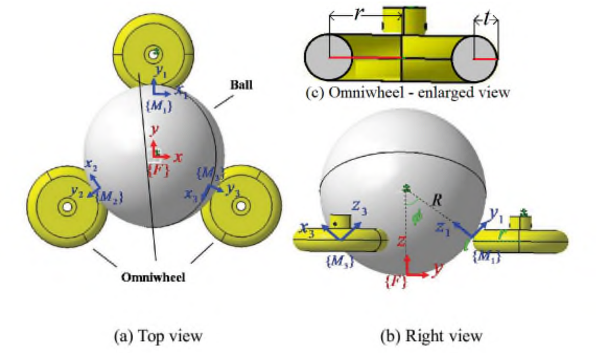

Figure 2. Coordinate systems of omniwheels {M} and ball {F}

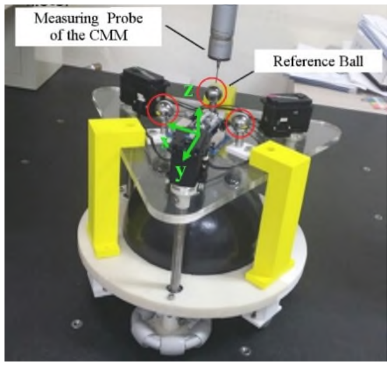

Figure 3. Experimental setup for posture evaluation

modifying the method suggested by Park et. al. [4]. The differential motion of the omniwheel with respect to the ball can be derived using the general form of equation 1.

$$\Delta_{M_i} = \left({}^{F}T_{M_i}\right)^{-1} \cdot \Delta_F \cdot {}^{F}T_{M_i}$$
$$= \begin{bmatrix} 0 & -\boldsymbol{\delta}_F \cdot \mathbf{w} & \boldsymbol{\delta}_F \cdot \mathbf{v} & \mathbf{u}\cdot\left(\boldsymbol{\delta}_F \times {}^{F}\mathbf{p}_{M_i} + \mathbf{d}_F\right) \\ \boldsymbol{\delta}_F \cdot \mathbf{w} & 0 & -\boldsymbol{\delta}_F \cdot \mathbf{u} & \mathbf{v}\cdot\left(\boldsymbol{\delta}_F \times {}^{F}\mathbf{p}_{M_i} + \mathbf{d}_F\right) \\ -\boldsymbol{\delta}_F \cdot \mathbf{v} & \boldsymbol{\delta}_F \cdot \mathbf{u} & 0 & \mathbf{w}\cdot\left(\boldsymbol{\delta}_F \times {}^{F}\mathbf{p}_{M_i} + \mathbf{d}_F\right) \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (1)$$

where, $\{M_i\}$ is i-th omniwheel coordinate system. Δ_{Mi} and Δ_F are differential motion matrices of the i-th omniwheel and the ball. ${}^{F}\mathbf{p}_{Mi}$ is the position vector of $\{M_i\}$ w.r.t $\{F\}$. **u, v, w** are direction vectors of $\{M_i\}$ w.r.t $\{F\}$. $\boldsymbol{\delta}_F = [\delta_x^F\ \delta_y^F\ \delta_z^F]^T$ is the rotational motion of $\{F\}$. $\mathbf{d}_F = [d_x^F\ d_y^F\ d_z^F]^T$ is the translational motion of $\{F\}$.

3.2. Calculation of velocity of omniwheels with respect to the ball

As shown in Figure 2, the point where the ball makes contact with the ground is considered the origin of the coordinate system of the ball $\{F\}$. $\{M_1\}$, $\{M_2\}$ and $\{M_3\}$ are used to mark the coordinate systems of the omniwheels 1, 2 and 3 which are placed 120 degrees apart on the circumference of the lower half of the ball. The distances between the center of the ball and the points of contact with the each omniwheel are considered as radius of the ball R. The actuation angle ϕ varies with the contact point between each omniwheel and the ball . The radius of the roller of the omniwheel is considered as t and the distance between the center of the omniwheel and the center of the roller is taken as r. The final velocity relationship between the ball and the omniwheels is given by equation 2.

$$\begin{bmatrix} v_{x,M1} \\ v_{x,M2} \\ v_{x,M3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -Rs\phi \\ -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} & -Rs\phi \\ -\dfrac{1}{2} & -\dfrac{\sqrt{3}}{2} & -Rs\phi \end{bmatrix} \begin{bmatrix} v_{x,F} \\ v_{y,F} \\ \delta_{z,F} \end{bmatrix} \quad (2)$$

where, $v_{x,M1}$, $v_{x,M2}$, $v_{x,M3}$ are the velocities of the omniwheels 1, 2 and 3. $v_{x,F}$ is the velocity of the ball in the x-direction, $v_{y,F}$ is the velocity of the ball in the y-direction and $\delta_{z,F}$ is the rotation of the ball in the z-direction.

4. Positioning Performance Evaluation

Positioning performance of the proposed ball-based robot was evaluated by using three reference balls attached to the top plate of the robot and using a coordinate measuring machine (CMM) as shown in Figure 3. From the three reference balls, the central position of the robot was calculated using the centroid method. Using the derived kinematics model, the robot was moved by actuating the motors with the calculated angular velocity. The position was measured and compared to the ideal posture. The error for two sets of readings are listed in Table 1. The leftmost column provides the angles of the three omniwheels and the rest of the columns are used to specify the error when comparing the ideal posture to the actual posture of the ball.

Table 1 Posture error measurement of the ball-based robot

ϕ_1 ϕ_2 ϕ_3 (degree)	Ball Direction	Ideal posture	Actual posture	Error
-29.656	x (mm)	-0.2824	-0.4579	0.1775
-29.128	y (mm)	0.0445	0.2494	0.2049
-29.216	γ (degree)	29.4168	28.9610	0.4558
56.76	x (mm)	50.0585	51.3404	1.2819
-29.392	y (mm)	-0.3557	-26.134	2.2577
-28.688	γ (degree)	0.1613	1.4512	1.2899

5. Conclusion and Future Work

A novel design for enhancing the structural stability of the ballbot was suggested in this paper. The kinematic relationship between the omniwheel and ball of the robot was established by using differential motion transformation. The positioning performance of the robot was evaluated using a CMM and its occurred error could be attributed to the slip due to improper contact between the omniwheel and ball. Some part of this error could be minimised by increasing the friction between the mating parts. Future work would include developing balancing capabilities for the robot using a suitable control mechanism. The kinematic relationship developed in the paper can be used for future applications where ball and omniwheel are used in tandem.

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