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A Practical Implementation of a Continuous Isotropic Spherical Omnidirectional Drive

David M Ball, *Member, IEEE*, Chris F Lehnert, Gordon F Wyeth, *Member, IEEE*

Abstract—**This paper presents a continuous isotropic spherical omnidirectional drive mechanism that is efficient in its mechanical simplicity and use of volume. Spherical omnidirectional mechanisms allow isotropic motion, although many are limited from achieving true isotropic motion by practical mechanical design considerations. The mechanism presented in this paper uses a single motor to drive a point on the great circle of the sphere parallel to the ground plane, and does not require a gearbox. Three mechanisms located 120° apart provide a stable drive platform for a mobile robot. Results show the omnidirectional ability of the robot and demonstrate the performance of the spherical mechanism compared to a popular commercial omnidirectional wheel over edges of varying heights and gaps of varying widths.**

I. Introduction

ROBOTS with an omnidirectional drive system have a distinct kinematic advantage over robots with a two wheel non-holonomic drive system. Robots with a holonomic omnidirectional drive have three independent degrees of freedom, thereby increasing mobility in cluttered and challenging environments. Service robots that operate in indoor environments can gain particular advantage by being able to move in arbitrary directions with arbitrary orientation.

The kinematic advantage of the omnidirectional drive robot can be limited if the mechanical implementation does not consider the challenges of working in human environments. Typical indoor environments have raised edges and gaps that can limit the mobility of the robot. Tadakuma and Tadakuma [1] provide examples of different raised edges and gaps that exist in the home and office environments such as at doorways between surfaces, the gap between the lift and the floor, cracks on the floor, and steps to assist handicapped walking. Well considered mechanical design can limit the interference these environmental obstacles will have on the robot.

The challenge addressed in this paper is to create an isotropic omnidirectional drive system that can negotiate typical edge and gap traversals obstacles in an indoor environment. The solution presented in this paper is based on the use of a set of three sphere wheels, each driven by an independent motor. The novel spherical wheel mechanisms are efficient in the use of volume, simple to manufacture, and provide an inherent mechanical transmission that removes the requirement for a gearhead on the motor. This paper presents results that illustrate the performance of the spherical isotropic system for edge and gap traversals compared to a popular omnidirectional wheel, the double transwheel.

The next section provides a review of omnidirectional mechanisms. Section III details our spherical drive, which is followed in Section IV by the experimental design and results of the studies, before the final section presents the paper's conclusion and raises possible future work.

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D. M. Ball is with the Queensland Brain Institute and the School of Information Technology and Electrical Engineering, The University of Queensland, Australia (email: dball@itee.uq.edu.au)

C. F. Lehnert and G. F. Wyeth are with the School of Information Technology and Electrical Engineering, The University of Queensland (email: christopher.lehnert@uqconnect.edu.au, wyeth@itee.uq.edu.au)

II. Existing Omnidirectional Mechanisms

Existing omnidirectional mechanisms may be broadly grouped into alternate, orthogonal, and spherical designs. The mechanisms differ in their isotropic ability, mechanical simplicity, continuity of contact, and volumetric efficiency. Isotropic ability refers to the drive system's ability to move uniformly in all directions.

The alternate design (see Fig. 1 for an example) was the earliest published method for creating an omnidirectional wheel [2], and consists of one large actuated wheel with smaller free spinning wheels around the circumference in one or many rows. These wheels are anisotropic, and are typically not continuous in the actuated direction. The continuous alternate wheel is a specialized version of the alternate wheel that enables continuous and smooth contact with the ground [3]. Alternate wheels are unable to negotiate relatively small edges, particularly at right angles to the direction of actuation due to the smaller rollers around the circumference of the larger wheel. Alternate wheels are unsuitable for typical indoor environments that have small step heights and step traversals. However, due to their mechanical simplicity, availability and price, and that the surface is flat and even, alternate wheels are popular with the robotics community especially in robot competitions such as RoboCup International [4] and RoboCup Junior.

Orthogonal wheels, shown in Fig. 1, were originally proposed by [5], and consist of multiple partial spheres that contact the ground for each mechanism. Typically, to minimize volume, only two wheels are used, which means that the ground contact shifts as the wheel spins 90 degrees.

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Orthogonal wheels have a discontinuous isotropic mechanism, allowing negotiation of step heights and gap traversals up to a limit in proportion to the diameter of the wheel. Increased diameter of the wheel is traded off against the increased volume of multiple large wheels and the effects of discontinuous contact with the ground that is separated by at least the wheel's diameter. The orthogonal mechanism can be built compactly, but only for operation on smooth surfaces [6].

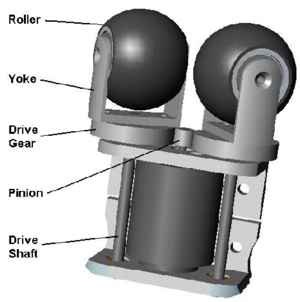

Fig. 1. (left) Alternate double row transwheel, (right) Orthogonal wheel.

The basis for a spherical wheel mechanism [7] is a sphere that contacts the ground surface, and is actively rotated in at least one direction and has at least another free rotational degree of freedom. West and Asada [8] provide two fundamental requirements for a spherical omnidirectional mechanism:

- *No over constraint and no sliding* – Each sphere must have two rotational degrees of freedom relative to the chassis such that it can roll in any direction on the floor. The sphere must have friction with the ground surface for traction force to prevent sliding.
- *Translational form closure* – The position of the sphere must be fixed relative to the chassis but does not imply any constraint to the rotation of the sphere.

The spherical mechanism provides the theoretically best continuous isotropic performance of the omnidirectional wheel types. However, the mechanical implementation can limit performance.

One approach to implementing the spherical omnidirectional mechanism, named omni-ball [1], is to separate the sphere into passively spinning hemispheres actuated by a central axle. Due to the split sphere, the mechanism is physically discontinuous and makes it closely related to the orthogonal wheel. Less obviously, this mechanism is not dynamically isotropic because as the sphere rotates in the active direction, the hemisphere's ground contact circumference size changes. The hemisphere's rotational singularity is addressed by using a small passive roller at the cost of increased mechanical complexity. The omni-ball is volume efficient as the mechanism is inside the sphere.

Other spherical mechanisms maintain a whole sphere for continuous isotropic performance and use an alternate wheel to provide active and passive motion to the sphere. The actuated direction of the alternate wheel actively rotates the sphere, while the free spinning rollers allow a free direction. The Rollmobs mechanism [9] has an alternate wheel that contacts the sphere's top hemisphere. Gravity provides the normal force between the sphere and the alternate wheel. The mechanism relies on contact with the ground for translational form closure. West [10] describes spherical mechanisms that feature rings of rollers, which are effectively alternate wheels with the passive rollers on the inside. There are two variants, one where the sphere slips on the rollers and is driven by the ring and another where the ring is freely rotating and uses another roller to directly actuate the sphere.

The implementation presented in [11] uses four sets of orthogonal wheels to provide active actuation and passive freedom of an omnidirectional drive vehicle that is balanced on a single sphere. A six axis force torque sensor allows the vehicle to sense the user's weight shift and maintain balance like an inverted pendulum.

Spherical mechanisms may also use rollers located on the sphere on the great circle that is parallel to the ground plane. Implementations exist with either two mechanisms (other support spheres maintain stability) [4], or three mechanisms [12]. Both robots use multiple actuators per mechanism.

III. Spherical Drive System

The spherical omnidirectional drive system described in this paper allows continuous isotropic motion, has translational form closure when in contact with the ground, and has few active components.

The mechanism, shown diagrammatically in Fig. 2 , has a single actuated roller located on the sphere on the great circle that is parallel to the ground plane (half way up the sphere in height). The actuated roller is parallel to the ground plane. The actuated roller rotates the sphere in the active direction due to the deformation of the rubber roller which creates a small contact surface allowing traction. The sphere rotates in the passive (slip) direction by rotating around the small contact surface with the actuated roller. This slip is possible because of the position of the actuated roller on the sphere. The roller is shaped to minimize the surface area in contact when the sphere rotates around the contact point. This design is in contrast to using an alternate or orthogonal wheel where the rollers allow the sphere's passive rotation. Our design is mechanically simpler and does not introduce the potential for sphere oscillations due to the discontinuous nature of the wheel. A CAD and picture of the mechanism is shown in Fig. 3.

The sphere's axis of rotation will change proportionally to the roller rotational speed and the motion of the remainder of the attached body. Kinematically, regardless of the sphere's rotational axis, the sphere will still continue to slip around the roller due to the traction coupling that cancels the effect of the rotation in the actuated direction.

There are three other types of contact with the sphere; passive rollers, support ball transfer units (also called spherical bearings), and closure ball transfer units. The passive rollers are positioned on the same great circle as the actuated drive roller and have a single degree of freedom. The support ball transfer units are located in the top hemisphere, and support the sphere against the robot's mass. The closure ball transfer units are located in the bottom hemisphere and prevent the ball from dropping out of the mechanism in the absence of a ground surface. Ball transfer units are preferred over a static piece of material as the sphere is more able to maintain its current rolling state.

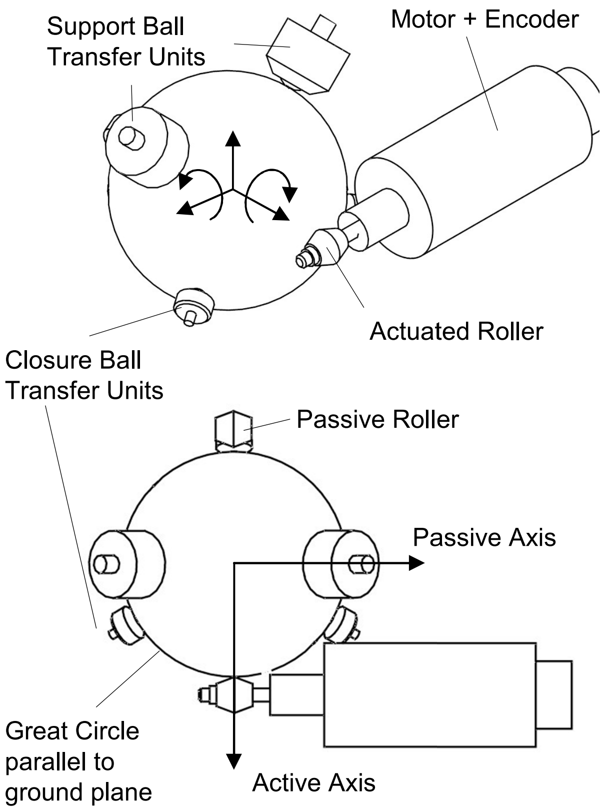

Fig. 2. These diagrams show the major mechanical design features of the spherical mechanism presented in this paper. (top) Isometric view, (bottom) top view.

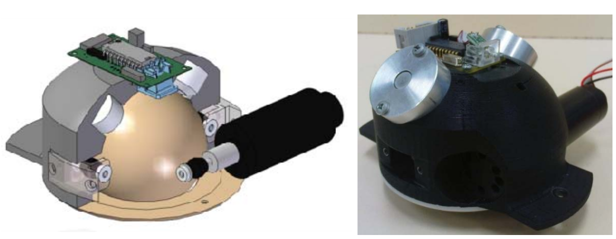

Fig. 3. Isometric view of the mechanism (left) CAD, (right) actual. Note that some features shown in the CAD were to allow for feature exploration.

In our implementation, the sphere is 50mm in diameter and is made of solid 70 shore A durometer type rubber. The support ball transfer units are of type Omnitrack 9001 and the closure ball transfer units are of type SKF 11MI-05-17. The actuator is a Faulhuber 2342 12 watt motor with a 512 count encoder mounted on the motor output shaft. The 8mm diameter (at the contact point) rubber roller is coupled directly to the motor output shaft which gives a transmission ratio of 6.25:1.

As shown in Fig. 4, the robot drive system is three spherical mechanisms separated by 120 degrees, the lowest number of ground surface contact points for a stable robot. As each mechanism uses a single actuator the robot requires only three actuators. This is in contrast to the other spherical robots that use multiple actuated rubber rollers per mechanism. This translates into savings in component cost, manufacturing cost, and the volume required to house the mechanism.

In our prototype robot, shown in Fig. 5, the clearance between the ground surface and the robot's bottom plate is 9mm, although this clearance can be raised to near half the diameter of the spheres (limited by the radius of the motor).

The drive system is mechanically simpler than similar mechanisms such as the removal of the ring of rollers compared to [8] and the use of only one actuator per spherical mechanism when compared to [4] and [12].

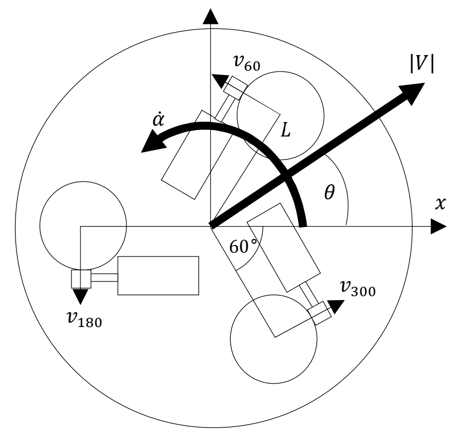

Fig. 4. This figure is a top down diagram of the robot drive system showing where the spherical mechanisms are located.

Given Fig. 4, and the general equation for omnidirectional wheels given in [13], the robot kinematics are given by:

$$v_{60} = |V|\left(-\frac{\sqrt{3}}{2}\cos\theta + \frac{1}{2}\sin\theta\right) + \dot{\alpha}L \quad (1)$$

$$v_{180} = |V|\sin\theta + \dot{\alpha}L \quad (2)$$

$$v_{300} = |V|\left(\frac{\sqrt{3}}{2}\cos\theta + \frac{1}{2}\sin\theta\right) + \dot{\alpha}L \quad (3)$$

where v is the velocity of the wheel at the specified angle, L is the distance from the centre of the robot to the centre of the sphere (75mm), $\dot{\alpha}$ is the robot's angular velocity, and $|V|$ is the magnitude of the translational velocity in direction θ.

The robot's control system takes commands that describe a change in position, a change in orientation, and a change in the direction of travel with respect to the local robot frame, as well as starting and stopping velocity references. Based on the command set and the kinematic equations (1, 2, 3) the trajectory generator generates a trapezoidal velocity profile for each wheel based on a 1 ms time step using defined acceleration parameters. Each motor's feedback control system then seeks to match the actual wheel velocities, as given by the motor's encoders, to the desired velocities.

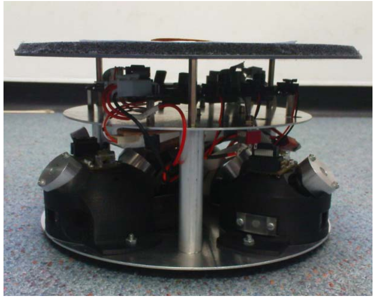

Fig. 5. Side view of the robot platform showing two of the three spherical mechanisms and motor drive electronics.

IV. Studies

A. *Study 1 - Verification of the mechanism*

This study demonstrates the robot's omnidirectional ability to simultaneously translate and rotate. The robot was commanded to translate 0.8m at a 0^{o} direction of travel while rotating 360^{o}. Fig. 6 shows the generated desired wheel velocities and the actual velocity tracking performance as given by the motor encoders.

During this movement the robot's position was tracked using an overhead vision system [14] running at 30Hz which gives a perspective and lens corrected (x, y, θ), filtered over 10 readings. Fig. 7 shows a comparison between the robot translational and rotational motion as determined by the robot's motor encoders (calculated with the inverse Jacobian), and the overhead tracking system.

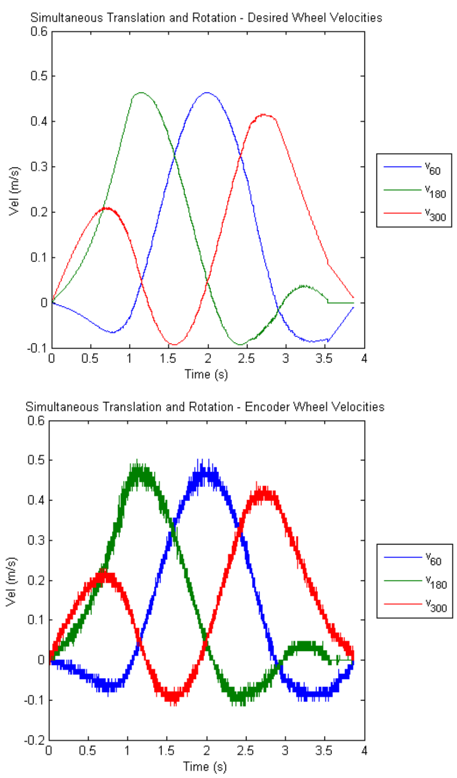

Fig. 6. These figures show the wheel velocities for a robot translating forward 0.8m while simultaneously rotating 360 degrees. (top) Desired velocities of the sphere generated by the kinematics, (bottom) actual sphere velocities as given by the motor encoders.

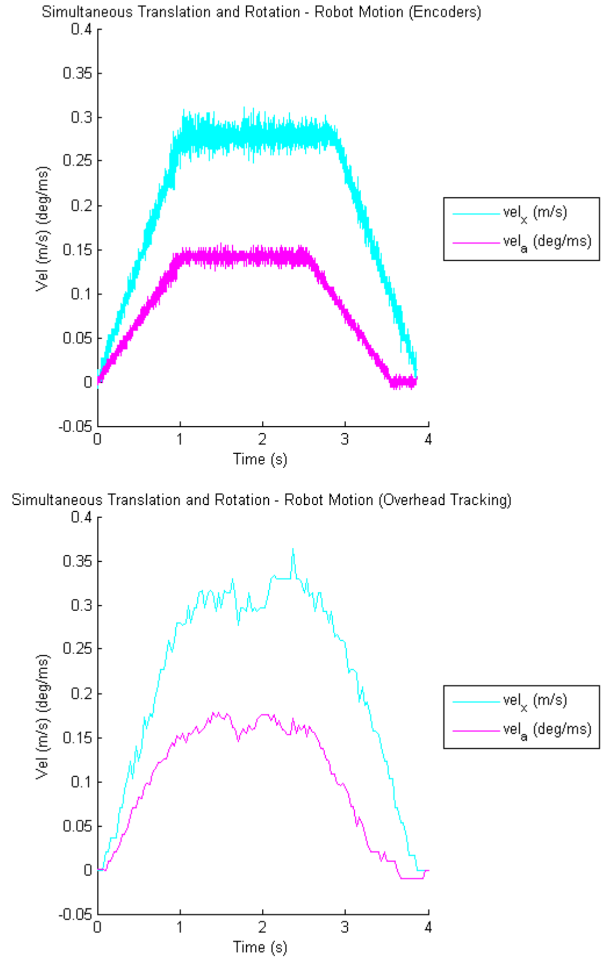

Fig. 7. These figures show the robot velocities for a 0.8m translation and 360 degree rotation. (top) As given by the robot's encoders, (bottom) as given by the overhead tracking system (filtered).

B. *Study 2 – Spherical versus Transwheel*

This study compared the performance of our mechanism with a popular commercial omnidirectional wheel, the double transwheel in step edge and gap traversal experiments. The transwheel has approximately the same outer diameter as the sphere diameter (50mm) and the exposed height of the smaller rollers for the double transwheel is 4.5mm.

1) Step Edge

The spherical and transwheel robots were given commands to translate across edges of varying height. The robots drove forward 1.5m, travelling across the test part at 0.3m/s without any global feedback. The robot was commanded to maintain a 0^{o} global orientation. Fig. 11 shows the results for the two step edge experiments, 4.5mm and 7mm, for three tests of both robots. The results show that once the height of the step is greater than the exposed height of the transwheel roller the gap either prevents the robot from translating beyond the step or causes a large error in its final position. In contrast, the results show the spherical omnidirectional drive maintains a similar level of accuracy to the final position regardless of the step height.

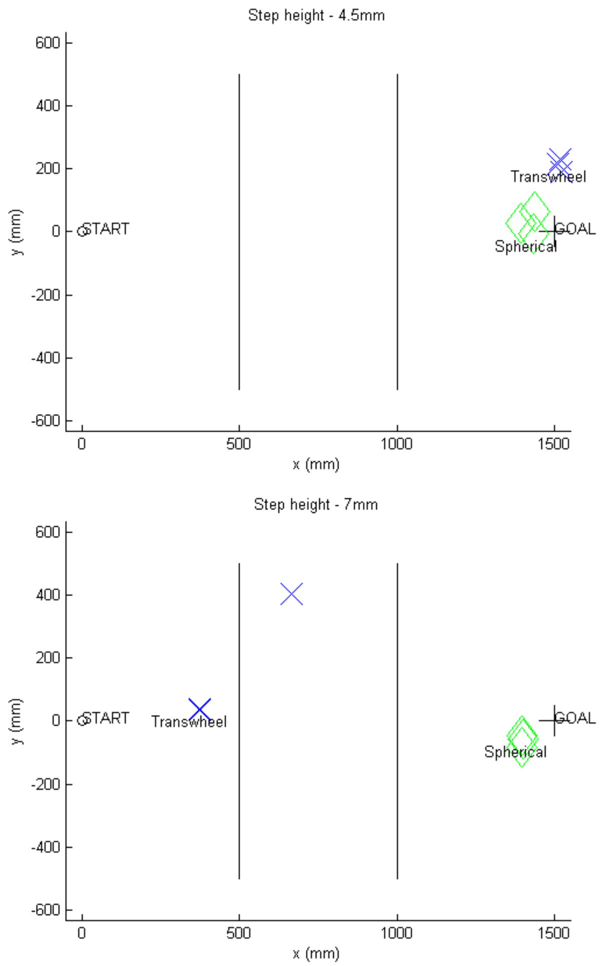

Fig. 8. Spherical versus transwheel robot step experiment. (top) 1.5mm and (bottom) 7mm. The vertical lines mark the step up and step down locations.

Fig. 9 shows the spherical robot's wheel velocities and robot velocities for the step obstacle experiment. The figure shows when each wheel reaches the rising and falling step edges as the burst of high amplitude oscillation. These results show the robot's wheel velocity control loop is able to quickly stabilize the velocity after the edges.

1) Gap Traversal

The spherical and transwheel robots were commanded to drive forward 0.7m across a gap obstacle, travelling across the gap at 0.3m/s without any global feedback. The robot maintains a 0 degree orientation. Fig. 10 shows the results of the gap traversal experiments for 20mm and 40mm wide gaps. The results show that as the gap becomes wider than the width of the transwheel this robot is unable to overcome the obstacle resulting in a large error in its final position. The results also show a neglgible decrease the accuracy of the spherical robot's final position as the width of the gap increases, even to 80% of the diameter of the sphere.

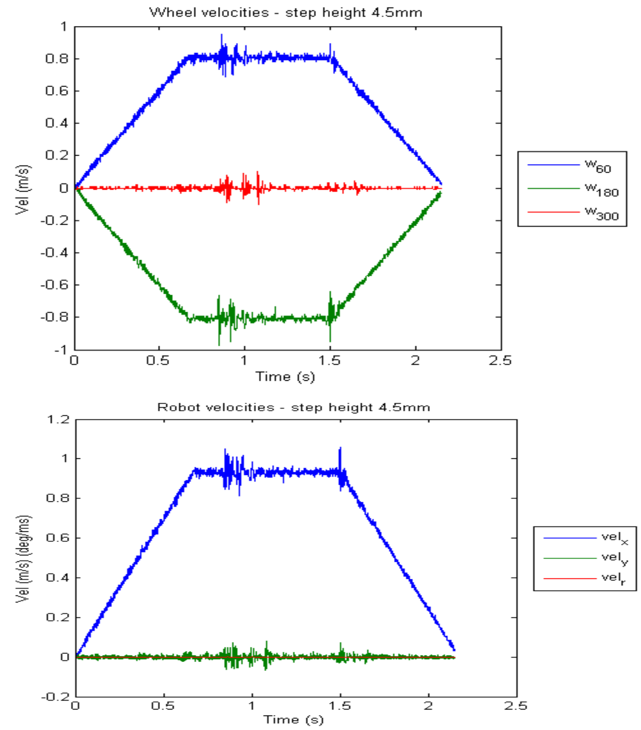

Fig. 9. Step height experiment with the spherical robot showing (top) wheel encoder velocities, and (bottom) the robot's velocity, transformed from the wheel encoder measurements. The graph shows the high amplitude oscillation that occurs as the wheel hits the edges.

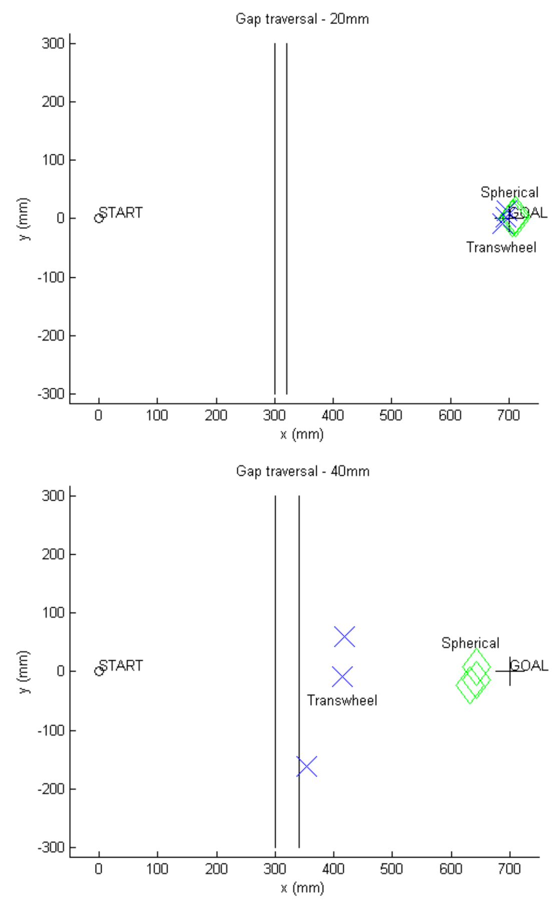

Fig. 10. Spherical versus transwheel mechanism gap traversal study, (top) 20mm gap, (bottom) 40mm gap. The vertical lines define the gap.

C. Study 3 – Dynamic Limitations

Fig. 11 demonstrates the behavior of the robot for varying accelerations and top velocities of a straight line trajectory across a smooth surface. The curves show that the robot tends more to the right as the acceleration and top velocity are increased. The trajectories are grouped by top velocity for accelerations of 2m/s^2 and above, indicating that there is a limit to the effect of increasing acceleration and the curve becomes proportional to the time spent accelerating. The figure also shows a gentler curve to the left during the constant velocity stage of the trapezoid.

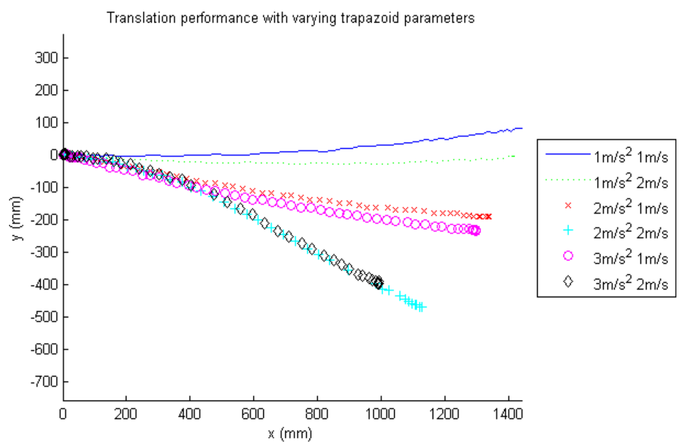

Fig. 11. This graph shows the overhead tracked motion of the robot for the same commanded translation for varying accelerations and top velocities. Note the curve to the right during the acceleration stage and the gentler curve to the left while maintaining top velocity.

This behavior is thought to be due to asymmetric slip between the sphere and the drive roller across the three spherical mechanisms. This slip difference would likely be caused because of the difference between each mechanism's actuated angle and the robot body acceleration angle which will affect the force that the sphere has on the drive roller. This means that as acceleration is increased the movement error while accelerating will increase. This issue could be resolved by actuating the opposite roller either by using another motor or more cheaply by using a gear or pulley mechanism. An attempt to use springs to resolve had negative side effects; with too high spring tension, the power needed to drive the wheel increases substantially; with too little tension, the ball moves away from the drive roller, and with the tension set in between, the sphere oscillates. User controlled pneumatic actuators [12] could be used to regulate a constant force against the roller but would increase the mechanical complexity. Alternatively, the drive system could use a predictive dynamic model to give wheel velocities that would account for the slip.

V. Conclusion

This paper has described a continuous isotropic spherical omnidirectional drive system. The spherical mechanism works due to the placement of the actuated roller on the great circle that is parallel to the ground plane which allows the sphere to be rotated in the active direction, and slip around the roller in the passive direction. The robot drive system is similar in concept to other spherical drive systems but is mechanically simpler and uses fewer actuators and therefore minimizes volume while maintaining similar drive characteristics.

The paper has demonstrated the robot's omnidirectional ability by tracking the wheel and robot velocities while simultaneously translating and rotating, and have showed the superior performance of our spherical mechanism over a popular alternate wheel, the double transwheel, for realistic edge and gap traversals. However, the last study has demonstrated the limits of mechanism for highly dynamic motion. Future work will model the dynamics of the mechanism and robot, to seek methods to normalize robot motion at varying accelerations and top velocities.

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