AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

CONF-9404137--2

OMNIDIRECTIONAL HOLONOMIC PLATFORMS*†

François G. Pin‡ and Stephen M. Killough§
Oak Ridge National Laboratory
P.O. Box 2008
Building 6025, MS-6364
Oak Ridge, TN 37831-6364, USA

*Patent pending. For further information regarding licensing contact the authors.

Contact: Dr. François G. Pin, Bldg. 6025, MS-6364, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6364, U.S.A., Telephone: (615)574-6130, Fax: (615)574-7860, E-mail: pin@ornl.gov

To be published in the Proceedings of the Twelfth Symposium on Energy Engineering Sciences, Argon..e, Illinois, April 27–29, 1994

† Research sponsored by the Office of Engineering Research Program, Basic Energy Sciences, of the U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

‡ Center for Engineering Systems Advanced Research (CESAR), Autonomous Robotic Systems Group, Engineering Physics and Mathematics Division.

§ Robotics and Process Systems Division.

OMNIDIRECTIONAL HOLONOMIC PLATFORMS

François G. Pin and Stephen M. Killough
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6364, USA

ABSTRACT

This paper presents the concepts for a new family of wheeled platforms which feature full omnidirectionality with simultaneous and independently controlled rotational and translational motion capabilities. We first present the "orthogonal-wheels" concept and the two major wheel assemblies on which these platforms are based. We then describe how a combination of these assemblies with appropriate control can be used to generate an omnidirectional capability for mobile robot platforms. The design and control of two prototype platforms are then presented and their respective characteristics with respect to rotational and translational motion control are discussed.

INTRODUCTION

A large number of wheeled or tracked mechanisms exist to serve as mobility platforms for teleoperated and/or autonomous robot vehicles [1]. For large and heavy outdoor robots, four-wheel, car-like driving mechanisms or skid-steer platforms have traditionally been used. Because the non-holonomic constraint* on their wheel mechanisms prevents sideways movements (also termed "crab motion") without preliminary maneuvering, these vehicles are quite restricted in their motion [2],[3],[4], particularly when operating in tight environments. Improvements in motion capabilities have been derived from the use of two independent driving wheels supplemented by casters (e.g. see robot in Ref. 5), two steerable and independently driving wheels [6], or three steerable and coordinated driving wheels (e.g. see robots in Refs. 7 and 8). The former type allows rotation of the platform around any point but does not allow sideways motion, while the second and third types realize both rotation of the platform and sideways motion through coordinated steering of the wheels. In these latter systems, however, the controls of the translational and rotational motions are not fully decoupled or independent, in the sense that very stringent compatibility conditions exist between the steering and driving velocities of the wheels [9]. To achieve the full three degrees of freedom of planar rigid body motion, these platforms must therefore be controlled as strongly constrained systems (e.g. see [10]), and any slight error in their control or actuation subsystems that violates the constraint will result in wheel slippage and accumulation of positioning errors.

A variety of mechanisms, inspired from the "universal wheel concept," (e.g. see Refs. 1 and 11) have been used to remedy some of the steerable wheel's friction and inter-wheel constraint problems in designing omnidirectional vehicles. The most common type of universal wheels, discussed in detail in Ref. 1, involves a large wheel with many small rollers mounted on its rim. As the drive shaft turns, the wheel is driven in a normal fashion in a direction perpendicular to the axis of the drive shaft, i.e., in the constrained direction of motion. At the same time, the small rollers allow the wheel to

* A non-holonomic constraint is a non-integrable constraint of the form $G(\overline{q}, \dot{\overline{q}}) = 0$, binding configuration variables and their derivatives. Because the constraint is not integrable, it does not affect the space of achievable configurations, $\overline{q}$, of the system, but it restricts the space of achievable velocities $\dot{\overline{q}}$ at given configurations.

freely move parallel to the drive shaft, providing the unconstrained direction of motion. Wheels of this type must be relatively large to accommodate the rollers and greatly suffer from the successive shocks caused when individual rollers make contact with the ground. A variation of this universal wheel incorporates elongated rollers which are positioned at 45° from the axis of the main shaft of the wheel, and are tapered to remedy some of the roller shocks. Four such wheels, however, are typically utilized to provide an omnidirectional capability to a platform (e.g. see Ref. 11) which, since one of the wheels can temporarily lose contact with the ground on uneven terrain, may lead to significant odometry and position tracking problems. Another interesting concept utilizing two rows of full spheres as rolling units has recently been introduced and demonstrated for omnidirectional platform motion [12]. The balls or spherical tires are arranged in two conveyor belts which produce forward and rotational motion of the platform in a manner similar to that of "skid-steer" vehicles. In addition, two controlled rods in each track contact the top of the balls and, by rotating around an axis parallel to the track, provide sideways motion of the platform. The rotational degree of freedom of these platforms, however, is extremely difficult to control since, like all tracked or "skid-steer" vehicles, significant sideways slippage of part of the track must occur during turns. Controlling or compensating for this tire slip on not perfectly uniform terrains does not appear feasible with the proposed design [12] and significant wear and tear of either the spherical tires or internal rods are expected on rugose ground surfaces.

In the following sections, we present a novel "orthogonal-wheels" concept which provides normal traction in a given direction while being free-wheeling in the other perpendicular direction. We describe the two major possible types of wheel assemblies based on this concept and then show how a combination of several of these orthogonal-wheels assemblies can be used to generate an omnidirectional capability. We present two prototype platforms which we developed based on these concepts and which feature full omnidirectionality with independently controlled rotational and translational degrees of freedom. The respective characteristics of each design are described and their applicability to various robotic platforms is discussed.

THE ORTHOGONAL-WHEELS CONCEPT AND MAJOR ASSEMBLIES

The basic operating principle of the orthogonal wheel concept is illustrated in Figure 1. The major components are two spheres of equal diameter which have been sliced to resemble wide, rounded-tire wheels, such as those that can be found on most ATV's (All Terrain Vehicles). The axle of each wheel is perpendicular to the sliced surfaces and is mounted using ball bearings so that the wheel is freewheeling around its axle. Through a bracket which is holding the extremities of the wheel axle, each wheel can be driven to roll on its portion of spherical surface, rotating around an axis Z perpendicular to the wheel axle. When these axes (Z_1 and Z_2, coming out of the figure plane in Figure 1a) are maintained parallel and at a constant distance from each other, and when the wheel rotations around these axes are synchronized, contact with the ground can be assured by at least one wheel, while allowing enough space for the brackets holding the wheel axles to clear the ground. The end-view sketch in Figure 1a shows the simplest configuration consisting of two identical wheels with 90° rolling surfaces on each and with axles offset by 90°, rotating at the same angular velocity. Note that a variety of other configurations based on different numbers or slicing of the spheres or various rotational speed patterns could also provide the required contact synchronization. In principle, the proper operation of the system has no requirement other than the parallelism of the Z rotational axes of the wheels, constant spacing with the ground of the spheres' center, and the synchronized successive contact of the wheels with the ground.

When the wheels are rotating in synchronized fashion they are driven in the direction perpendicular to the Z axes. In the mean time, whatever wheel is in contact with the ground can roll freely in the direction parallel to Z, therefore allowing the entire wheel assembly to move freely in that direction. The two (or more) wheels do not necessarily need to be close to each other, although from a practical point of view, their proximity will minimize drive train and assembly parts. Two preferred configurations for assembling the type of orthogonal wheels shown in Figure 1 are discussed in the following paragraphs.

In the "longitudinal" orthogonal-wheel assembly, shown in Figure 2a, the two rotating axes (labeled Z_1 and Z_2 in Figure 1) of the wheels are merged so that the two brackets holding the axles can be mounted at 90° from each other along the axis of a common shaft. The extremities of the shaft are held in vertical plates (with ball bearings) which provide the attachment points for the assembly underneath the platform. One end of the shaft is connected to a motor which, by rotating the shaft, provides the driving of the wheel assembly. When the motor turns, the wheels provide traction in the direction perpendicular to the motor shaft, while they remain freewheeling in the direction parallel to the shaft.

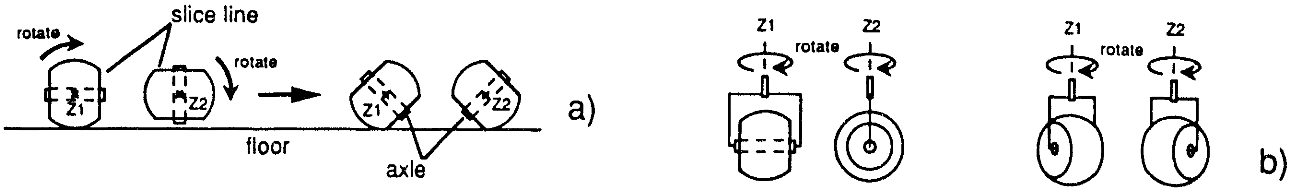
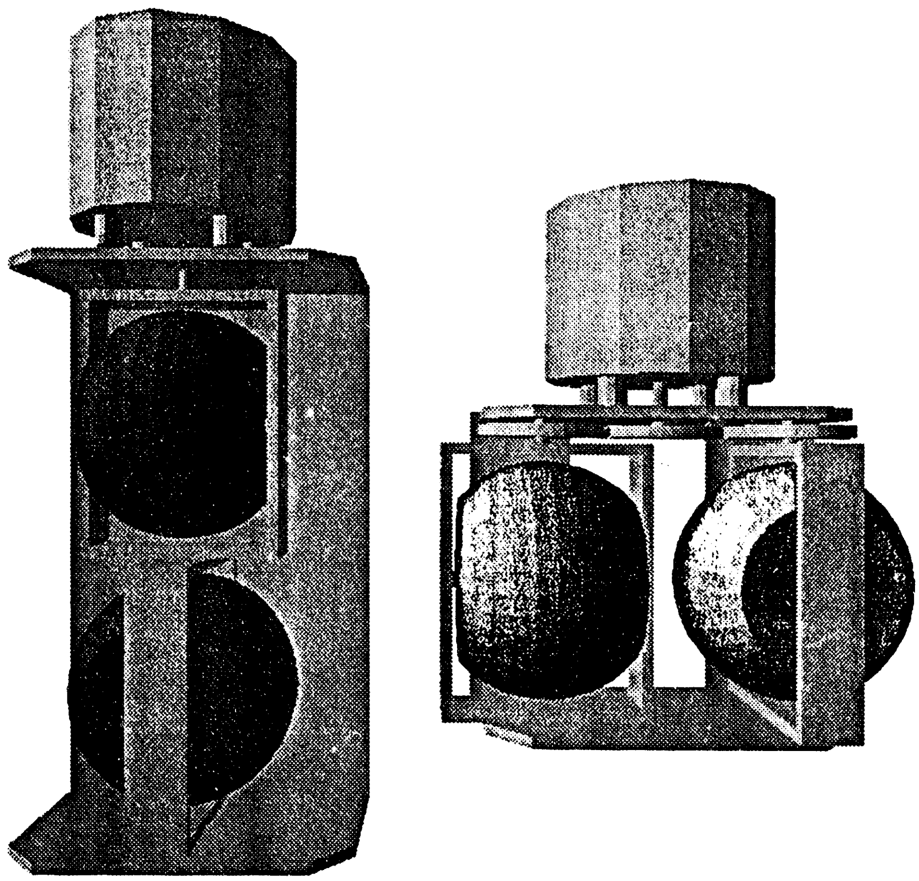


Figure 1. Schematic of the Basic Orthogonal-Wheels Operating Principle: a) End-View, b) Top-View



(a) (b)

Figure 2. Three-Dimensional Perspectives of a) the "Longitudinal" and b) Orthogonal-Wheel Assembly

The "lateral" assembly of orthogonal wheels is the most obvious from the diagrams of Figure 1, however its construction is slightly more complicated since it requires a gear- or belt-type transmission. A 3-D perspective of this assembly is shown in Figure 2b. Each wheel axle is held by a bracket which is coupled to a driving shaft. These two driving shafts are parallel and therefore can be coupled by gears or by a transmission belt to a common motor, so that they always turn at the same velocity. The assembly thus has a constrained and controllable motion in the direction perpendicular to the shafts while it is freewheeling in the direction parallel to the shafts. Use of this "lateral" arrangement of the wheels has been proposed for some mechanisms with bi-directional motion capabilities [13]; however, as we showed in [14], not only can full 3 d.o.f. omnidirectionality be achieved with proper control of the constrained and unconstrained directions of motion, but also rotation of this assembly around any vertical axis takes place with no slippage of the wheels and without discontinuity in the motor speed [14].

Both lateral and longitudinal wheel assemblies can be used in the same manner to provide an omnidirectional capability to platforms: when placing two or more of these assemblies underneath a platform, their respective motion in constrained directions can be combined to produce a motion of the platform in any desired direction, while each assembly freewheels in its unconstrained direction.

The only requirements are that the layout provide enough directions of constrained motions of the assemblies to allow both omnidirectional translation and rotation of the platform, and that stability of the platform be maintained independently of the internal configuration of the assemblies, i.e., which wheel in each assembly makes ground contact. To produce a platform with three full degrees of freedom, the simplest layout with no kinematic redundancy requires three assemblies of the type shown in Figure 2a or 2b. With the three assemblies located at the three apexes of a triangle, the platform load stability is extremely easy to ensure, while a 120° orientation relationship between the three constrained motion directions provides excellent directional control capability. The schematics of two such layouts using longitudinal and lateral wheel assemblies are shown in Figures 3a and 3b, respectively. Note that, without the benefit of a suspension system, a layout with four perpendicular assemblies would not provide added load carrying capability and, in some cases, would invalidate the directional control because of the possibility for non-contact of one of the wheels on uneven grounds.

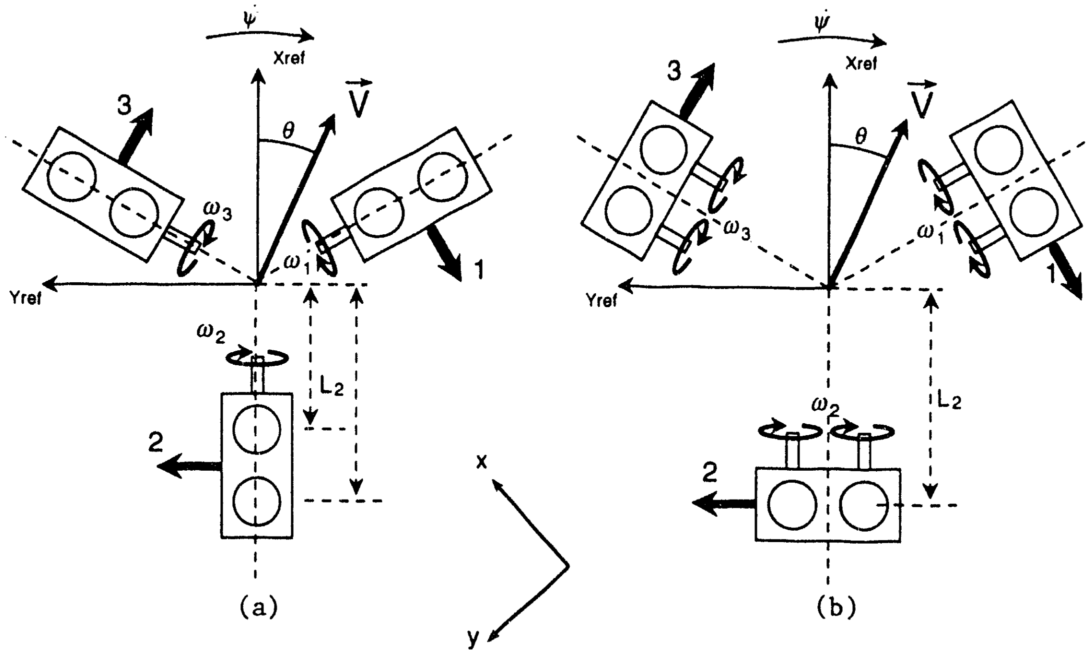


Figure 3. Schematic of the Basic Layout for 3 D.O.F. Motion Using a) Longitudinal and b) Lateral Orthogonal-Wheel Assemblies

OMNIDIRECTIONAL PLATFORM MOTION CONTROL

In both schematics of Figure 3, the constrained directions of motion of each assembly are indicated by the arrows labeled 1, 2, and 3. For each layout, let $\dot{\psi}$ denote the angular velocity (in rad/sec) of the internal reference frame of the platform (X_{ref}, Y_{ref}) with respect to an absolute reference frame (x, y). The magnitude of the platform translational velocity (in m/sec) is denoted by $|V|$ and its direction with respect to the platform internal reference frame is denoted by $\Theta \in [0, 2\pi]$. With these conventions, the wheels' driving shaft velocities, w_i, can be calculated (in rad/sec) for either layout in Figure 3 as:

$$w_1 = \frac{|V|}{2R}(\sin\,\Theta - \sqrt{3}\,\cos\,\Theta) + \frac{\dot{\psi}L_1}{R} \tag{1}$$

$$w_2 = -\,\frac{|V|}{R}\,\sin\,\Theta + \frac{\dot{\psi}L_2}{R} \tag{2}$$

$$w_3 = \frac{|V|}{2R}(\sin\,\Theta + \sqrt{3}\,\cos\,\Theta) + \frac{\dot{\psi}L_3}{R} \tag{3}$$

where R is the radius of the spherical wheels and L_i represents the distance between the center of the platform and the center of the wheel of assembly i currently contacting the ground. The first terms on the right-hand side of Eqs. (1) to (3) represent the projections of the translational velocity $|V|$ on the constrained motion directions of each assembly, while the last terms represent the components due to the rotational velocity of the platform.

Equations (1) and (3) represent a very convenient formulation of the platform kinematics for the sensor-based and trajectory-tracking control modes. In teleoperation and for odometry calculations, a slightly modified form of these equations can be used, which clearly illustrates the one-to-one relationship which exists between the Cartesian and joint velocities: if we set

$$V_x = |V| \cos \Theta \tag{4}$$

$$V_y = |V| \sin \Theta \tag{5}$$

Equations (1) to (3) can be written as:

$$(w_1, w_2, w_3)^T = A \; (V_x, V_y, \dot{\psi})^T \tag{6}$$

with

$$A = \frac{1}{R} \begin{pmatrix} \frac{-\sqrt{3}}{2} & \frac{1}{2} & L_1 \\ 0 & -1 & L_2 \\ \frac{\sqrt{3}}{2} & \frac{1}{2} & L_3 \end{pmatrix} \tag{7}$$

Since L_1, L_2, and L_3 are always positive quantities, A is invertible and its inverse matrix A^{-1} is:

$$A^{-1} = \frac{R}{L_1 + L_2 + L_3} \begin{pmatrix} \frac{-2L_3 - L_2}{\sqrt{3}} & \frac{L_1 - L_3}{\sqrt{3}} & \frac{2L_1 + L_2}{\sqrt{3}} \\ L_2 & -L_1 - L_3 & L_2 \\ 1 & 1 & 1 \end{pmatrix} \tag{8}$$

so that

$$(V_x, V_y, \dot{\psi})^T = A^{-1} \; (w_1, w_2, w_3)^T \tag{9}$$

It is clear from these relations that the rotational and translational motions are fully decoupled and can be controlled independently and simultaneously. Moreover, there are no constraints on the space of achievable translational and rotational velocities of the platform, and Eqs. (1) to (3) or Eqs. (6) to (9) represent a bijective mapping between the sets of (w_1, w_2, w_3) and (Θ, $|V|$, $\dot{\psi}$) or (w_1, w_2, w_3) and (V_x, V_y, $\dot{\psi}$). In their three-dimensional space of planar motion (translation and rotation), both platforms illustrated in Figure 3a and 3b are thus omnidirectional and holonomic systems. Moreover, both platforms can fully access the three degrees of freedom of planar rigid body motions with no constraints or compatibility conditions on the three independent controls, a capability not achieved by any conventional wheeled system.

Although Eqs. (1) to (9) apply to either layout in Figure 3, the effect of the different characteristics of the assemblies with respect to rotation around a vertical axis are quite explicit here: for the case of Figure 3b using the lateral assemblies, the values of L_1, L_2, and L_3 are the same whichever wheel in the corresponding assembly is in contact with the ground, whereas in the case of Figure 3a, these values change when contact with the ground switches from one wheel to the other in the longitudinal assemblies. This is illustrated in Figure 3a by the two dimension arrows showing the two possible values of L_2. From the control point of view, rotational motion of the longitudinal assembly thus represents a challenge since the switch of contact from one wheel to the other and the corresponding step function in w_i have to be accurately tracked and implemented. As far as translational motions are concerned, the two layouts are kinematically equivalent (with the same constant coefficients in the first two columns of the matrix A). To produce platforms with omnidirectional translational capabilities only, the layout of Figure 3a using the much-simpler-to-fabricate longitudinal assembly would probably be preferred. For platforms needing full 3 d.o.f. motion with a rotational capability, the layout of Figure 3b using the lateral wheel assemblies should be selected because of the constant values of the L_i's and the much simpler control system.

To verify the proposed concepts, two experimental platforms were constructed, one with longitudinal, the other with lateral, wheel assemblies, each with an on-board computer-based control system. The computing hardware is composed of a VME bus with seven slots occupied by a 68020 CPU, a floppy controller, a hard disk controller, serial ports, D/A and A/D cards and a custom-designed VLSI fuzzy logic inferencing board [15],[16],[17]. Each orthogonal-wheel assembly is driven by a typical variable speed DC motor equipped with a tachometer to provide feedback to the velocity control. Data from the three tachometers are also fed back to the computer to perform the dead reckoning. The commands to the velocity control loops are provided at 100 Hz by the computer which receives input either from a joystick for operation in teleoperated mode, or from the path planning and tracking modules in autonomous mode.

In teleoperated mode, the signals from the joystick directly provide the values of $\dot{\psi}$, V_x, and V_y. The control system calculates the three shaft velocities from Eqs. (6) and (7) and servos on these at 100 Hz using the tachometer data. In autonomous mode, the input to the control system are either "target configurations" (x, y, ψ) which are provided by the user in a list of "via points" forming a trajectory, or "target speeds" $(|V|, \Theta, \dot{\psi})$ calculated by the reasoning systems at sensor sampling rate during sensor-based navigation. The inferencing modules that were developed for decision-making in sensor-based (autonomous) navigation and obstacle avoidance using a ring of twenty-four acoustic range sensors on the deck of the platform and the custom-designed VLSI fuzzy logic inferencing board, are described in detail in Refs. [17] and [18]. In the user-provided trajectory following mode, the target configuration is compared at every loop cycle to the current estimate of position and orientation calculated by the dead reckoning. The results provide the desired direction of motion and the platform target rotational and translational speeds using linear ramp up profiles, up to the preset maximum velocities. The motor velocities are then calculated using Eqs. (1) to (3). At each loop cycle (of length Δt), the dead reckoning system uses encoders on the wheel shafts to estimate the actual rotation of each wheel. With these values (and for the longitudinal assemblies, the values L_i obtained from the photosensors), the platform displacements are easily calculated from Eqs. (8) and (9).

To demonstrate the operationality of the orthogonal-wheels assembly concept and to test the control scheme and dead reckoning systems described in the previous section, a series of tests were performed in which a variety of trajectories, each specified as a list of "via points," were submitted to the testbed platform control system. Figure 4 shows the platform with "longitudinal" wheel assemblies during one of these tests made to illustrate its translational omnidirectionality. A pen attached to the side of the platform is used to display the trajectory consisting of points, approximately 3 cm apart, that were digitized from an actual hand-written note. The ability of the platform to translate in any direction is quite apparent, while that of rapidly changing direction of motion is demonstrated for example at the top of the letter "o" or the bottom of the letter "n." The trajectory was closed by asking the platform to "frame" the writing and return to its starting location. The error shown by the position of the pen when the platform stopped was about 2 cm for this trajectory which was about 6 m in length. As discussed and reported in [18], a variety of other trajectories, some involving rotational motions, were also used to investigate the accuracy of the dead reckoning system and the two platforms' path tracking capabilities, with observed errors always much less than 1% of the total displacements in the trajectory.

CONCLUDING REMARKS

An original orthogonal-wheels assembly concept which exhibits constrained and unconstrained directions of motion has been presented. Two possible assembly configurations of the wheels, labeled the "longitudinal" and "lateral" assemblies, have been discussed and their use in producing omnidirectionality of platforms through various combinations of their constrained motions has been described. A design has been proposed to produce fully omnidirectional and holonomic platforms with unconstrained, simultaneous, and independently controlled rotational and translational motions, and two prototype platforms have been constructed. Proof-of-principle experiments illustrating the orthogonal-wheels assembly concept and the platform omnidirectionality with simultaneous and independently controlled translational and rotational motions have been performed, suggesting that very accurate control of the omnidirectional translation motions can be obtained using either the "lateral" or "longitudinal" orthogonal-wheels assemblies, and that significantly better control of the platform rotational motions can be realized using the "lateral" type of assemblies at the cost of a slight additional complexity in the design of the drive trains.

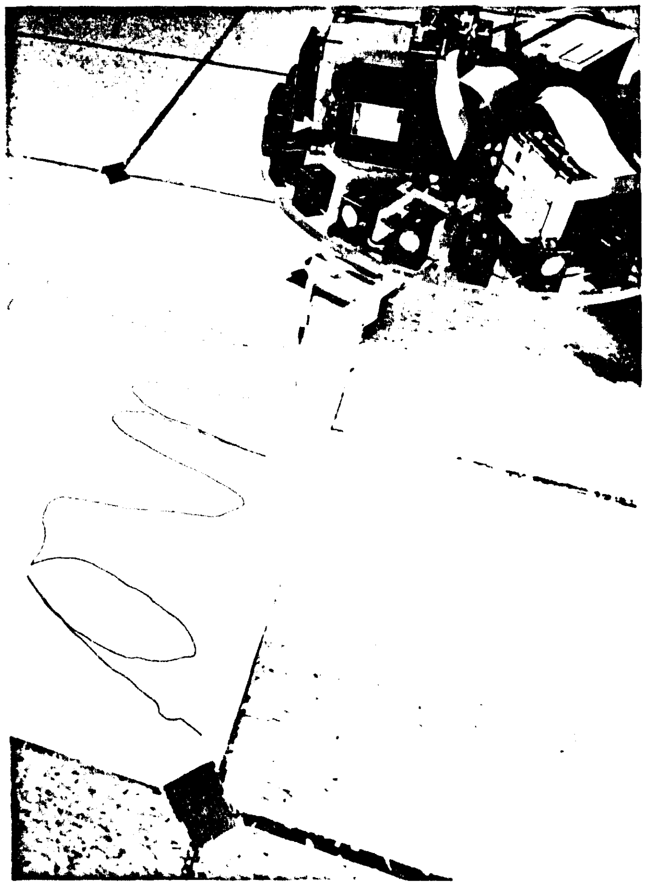


Figure 4. Platform performing a trajectory requiring translational omnidirectionality.

Besides their overall holonomy and omnidirectionality, the very important and unique characteristic of mobile platforms based on orthogonal-wheels assemblies is that the controls of their rotational and translational motions are fully decoupled. In other words, the platforms have three independent controls that can be used to fully access the three degrees of freedom of planar rigid body motions with no constraints or compatibility conditions on the controls. This feature, and the associated one-to-one relationship between Cartesian and joint velocities, is particularly interesting with respect to accurate path tracking and positioning since loop-rate errors in the actuation controls would result in platform positioning errors that are directly tractable with encoders, rather than in wheel slippage as is the case when steering and velocity compatibility conditions are even slightly violated in conventional wheel systems.

The basic platforms discussed in this paper can thus be viewed as omnidirectional, holonomic, statically stable, and fully controllable "casters." The fact that their omnidirectionality is achieved without the steering of wheels around a vertical axis (and the associated friction and possible tear) is particularly interesting for the design of large, possibly odd-shaped robotic platforms or vehicles having to operate and maneuver in constricted spaces. Furthermore, proper coordinated control of several of these low profile (small wheel well) casters underneath a large platform would in turn provide full omnidirectionality to that platform.

Another envisionable general area of applications would involve positioning the proposed rolling platforms "wheels up" in transporting or conveyor-type systems, or machine tool tables so that large packages, cargo-handling pallets, parts to be machined, etc., can be routed or accurately positioned. The omnidirectionality, decoupled controls, and no-wheel-slippage motion capabilities would allow precise and simultaneous translation and rotation of the transported materials without leaving undesirable scratches or friction marks.

REFERENCES

1. P. F. Muir and C. P. Neuman, "Kinematic Modeling of Wheeled Mobile Robots," *Journal of Robotic Systems* **4**, 281–340, 1987.

2. J. P. Laumond, "Feasible Trajectories for Mobile Robots with Kinematic and Environment Constraints," in *Proceedings of the Intelligent Autonomous Systems Conference*, Amsterdam, December 1986.

3. F. G. Pin and H. A. Vasseur, "Trajectory Generation for Autonomous Mobile Robots with Non-Holonomic and Steering Angle Constraints," in *Proceedings of the IEEE International Workshop on Intelligent Motion Control*, Istanbul, Turkey, August 1990, 295–299.

4. H. A. Vasseur, F. G. Pin, and J. R. Taylor, "Navigation of a Car-like Mobile Robot in Obstructed Environments Using Convex Polygonal Cells," in *Robotics and Autonomous Systems* **10**(2–3), 133–146 (1992).

5. C. R. Weisbin, G. de Saussure, J. R. Einstein, F. G. Pin, and E. Heer, "Autonomous Mobile Robot Navigation and Learning," *Computer* **22**(6), 29–35, June 1989.

6. F. G. Pin, M. Beckerman, P. F. Spelt, J. T. Robinson, and C. R. Weisbin, "Autonomous Mobile Robot Research Using the HERMIES-III Robot," in *Proceedings of the IROS International Workshop on Intelligent Robot and Systems*, "The Autonomous Mobile Robot and Its Application," Tsukuba, Japan, September 1989, 251–256.

7. R. C. Arkin, "Integrating Behavioral, Perceptual, and World Knowledge in Reactive Navigation," *Robotics and Autonomous Systems* **6**(1 & 2), 105–122, 1990.

8. Y. Koren and J. Borenstein, "Potential Field Methods and Their Inherent Limitations for Mobile Robot Navigation," in *Proceedings of the IEEE International Conference on Robotics and Automation*, Sacramento, California, April 1991, 1398–1404.

9. J. C. Alexander and J. H. Maddocks, "On the Kinematics of Wheeled Mobile Robots," *International Journal of Robotics Research* **8**(5), 15–27, 1989.

10. D. B. Reister and M. A. Unseren, "Position and Constraint Force Control of a Vehicle with Two or More Steerable Drive Wheels," *IEEE Transactions on Robotics and Automation* **9**(6), 723–731, 1993.

11. G. L. Blaisdell, "Performance of an Omnidirectional Wheel on Snow and Ice," *Naval Engineers Journal* **103**(1), 34–41, 1991.

12. M. West and H. Asada, "Design of a Holonomic Omnidirectional Vehicle" in *Proceedings of the IEEE International Conference on Robotics and Automation*, Nice, France, May 1992, 97–103.

13. W. Rose, "Powered Spheres 'Walk' and Roll," *Eureka*, 70–72, October 1988.

14. F. G. Pin and S. M. Killough, "A New Family of Omnidirectional and Holonomic Wheeled Platforms for Mobile Robots," accepted for publication in *IEEE Transactions on Robotics and Automation* (1994).

15. H. Watanabe, W. Dettloff, and E. Yount, "A VLSI Fuzzy Logic Inference Engine for Real-Time Process Control," *IEEE J. of Solid State Circuits* **25**(2), 376–382, 1990.

16. J. R. Symon and H. Watanabe, "Single Board System for Fuzzy Inference," in *Proceedings of the Workshop on Software Tools for Distributed Intelligent Control Systems*, September 1990, 253–261.

17. F. G. Pin, H. Watanabe, J. Symon, and R. S. Pattay, "Using Custom-Designed VLSI Fuzzy Inferencing Chips for the Autonomous Navigation of a Mobile Robot," in *Proceedings of IROS '92, the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Raleigh, North Carolina, July 1992, 790–795.

18. F. G. Pin and Y. Watanabe, "Steps Toward Sensor-Based Vehicle Navigation in Outdoor Environments Using a Fuzzy Behaviorist Approach," *International Journal of Intelligent and Fuzzy Systems* **1**(2), 95–107 (1993).