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ABSTRACT

This paper presents the concepts for a new family of wheeled platforms which feature full omnidirectionality with simultaneous and independent rotational and translational motion capabilities. We first describe the original "orthogonal-wheels assembly" on which these platforms are based and discuss how a combination of these assemblies is used to generate an omnidirectional capability. The design and control of a prototype platform developed to test and demonstrate the proposed concepts is then described, and experimental results illustrating the full omnidirectionality of the platform with decoupled rotational and translational degrees of freedom are presented.

I. INTRODUCTION

A large number of wheeled or tracked platform mechanisms have been studied and developed to provide their mobility capability to teleoperated and 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 of the kinematic constraints of these mechanisms,[2,3,4] these vehicles are restricted in their motion in the sense that they cannot move sideways (also termed "crab motion") without preliminary maneuvering. Better motion capabilities have been investigated in a variety of research centers and demonstrated on smaller laboratory robots. These improvements in motion capabilities typically are derived from the use of two independent driving wheels supplemented by casters (e.g. see robot in Refs. 5, 6, or 7) or three steerable and coordinated driving wheels (e.g. see robots in Refs. 8, 9, and 10). The former type allows rotation of the platform around any point but does not allow sideways motion, while the second type realizes both rotation of the platform and sideways motion through coordinated steering of the wheels. In the latter case, however, these two motions cannot occur simultaneously. Moreover, steering requires rotation of the wheels around a vertical axis which, for large vehicles equipped with wide tires, may generate significant sliding and friction of the wheels.

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A variety of other mechanisms, all based on the "universal wheel concept," (e.g. see Refs. 1 and 11) have been used to remedy some of the friction problems for omnidirectional vehicles. A "universal wheel" is an assembly which provides a combination of constrained and unconstrained motions when turning. When two or more of these wheels are mounted on a platform, their constrained and unconstrained motions can be combined to provide omnidirectionality. The most common type of universal wheels, illustrated Fig. 1, involves a large wheel with several small rollers mounted on the rim as its basic assembly.[1] As the drive shaft turns, the vehicle is driven in a normal fashion in a direction perpendicular to the axis of the drive shaft, i.e., in the constrained direction as labeled in the figure. At the same time, the small rollers allow the wheel to freely move parallel to the drive shaft or in the unconstrained direction. 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. Another type of universal wheel (e.g. see Ref. 11) utilizes 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. To our knowledge, however, none of these designs succeed in fully decoupling the rotational and translational degrees of freedom (d.o.f.) while providing an omnidirectional capability to the platform.

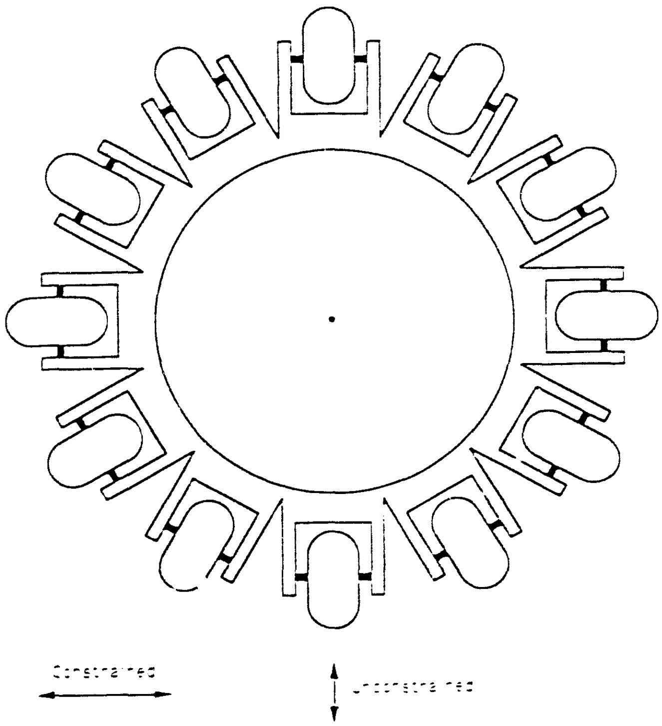


Fig. 1. Universal wheel consisting of several small rollers.

In the following section, we present a novel "orthogonal wheel" assembly which provides normal traction in a given direction while being free-wheeling in the other perpendicular direction. We then show how a combination of several of these orthogonal wheel assemblies can be used to generate an omnidirectional capability. In Section 3, we apply these concepts to the design of a prototype platform which includes full omnidirectionality with independent rotational and translational degrees of freedom. Some experimental results illustrating these characteristics are presented in Section 4 and concluding remarks about the applicability of the system to various robotic platforms are given in Section 5.

2. THE ORTHOGONAL WHEEL ASSEMBLY CONCEPT

A three dimensional view of the basic orthogonal wheel assembly is shown in Fig. 2. The major components of the assembly 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 held in a bracket using ball bearings so that the wheel is freewheeling around its axle. The two brackets are mounted at 90° from each other on the axis of the main 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. The end-view sketch in Fig. 3 shows how the slicing can be made to produce two identical wheels with 90° rolling surfaces on each, so that contact with the ground is provided alternatively by one ball or the other when the main shaft rotates, while allowing enough space for the brackets to clear the ground.

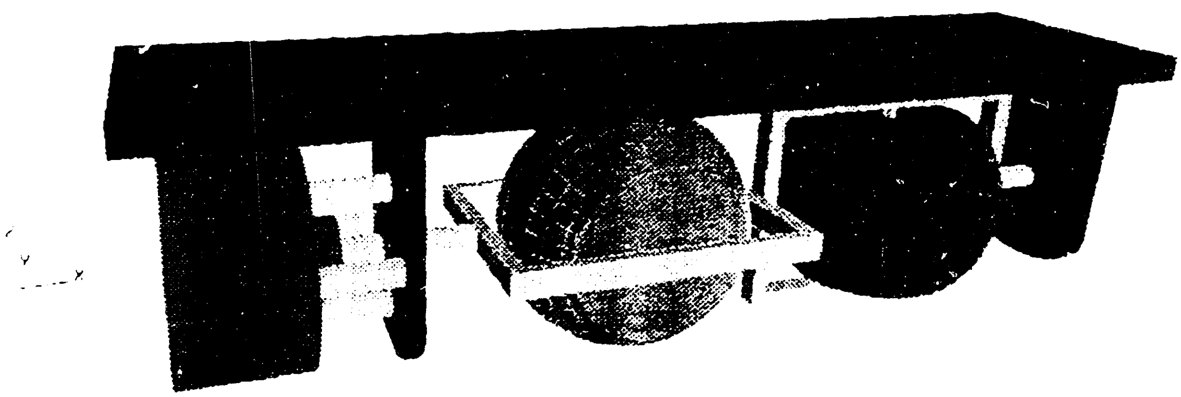


Fig. 2. "Longitudinal" wheel assembly using orthogonal ball wheels.

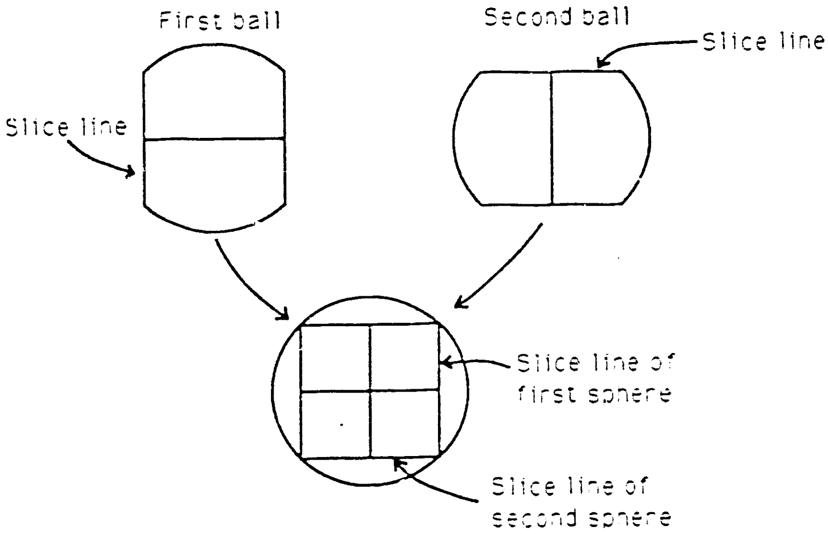


Fig. 3. End view of the orthogonal wheel assembly.

When the main shaft turns, the wheels provide traction in the direction perpendicular to the main shaft, i.e., in the direction labeled y in Fig. 2, while they are freewheeling in the direction parallel to the shaft, i.e., direction x in Fig. 2. In the direction perpendicular to the shaft, the entire assembly thus has a constrained motion which is controllable by the rotation of the main shaft, while the motion component in the direction parallel to the shaft is unconstrained. The advantages of this design over the universal wheels discussed in the previous section are: fewer needed parts, smaller wheel-well size requirements and smoother contact with the ground. Note that as long as the entire assembly does not rotate around a vertical axis, there is no requirement for a single contact point since both wheels turn at the same velocity and have identical trajectories on the ground. This is an interesting feature for building platforms with omnidirectional translation capability only (the rotation of the upper body being provided by another independent motor above the wheel chassis as is common in platforms with three steerable wheels) since an overlap of the rolling surfaces of the two balls is feasible to provide a very smooth rolling behavior of the whole assembly. If rotation of the assembly around a vertical axis is desired, then a single point of contact is required to prevent slippage of one of the wheels. For the prototype platform described in the next section, a regular machining accuracy of .001 inches (.025 mm) and the natural taper of the edge of the thin rubber films that were used on the metallic balls to improve traction provided excellent behavior during the switches of contact from one wheel to the other. As detailed in the following section, the challenge with the "longitudinal" wheel arrangement shown in Fig. 2 when rotating around a vertical axis resides with how precisely the *time* of the contact switch can be detected, and how well the change in shaft velocity required at the switch of contact can be approximated through the control system. If the inertia of the motor and/or the wheels is so great that a good approximation is not feasible (generally resulting in a jerk in the motion and possibly in significant positioning errors), then a "lateral" assembly of the wheels can be used which remedies this problem with some slight additional complexity in the drive train.[12,13,14] Consider the upper position of Fig. 3. The axle of the ball on the left is horizontal and its bracket could be in a horizontal plane coming out of the figure. The bracket of the ball on the right would thus be in a vertical plane also coming out of the figure. Each bracket could be coupled to driving shafts that would be parallel to each other and coming out of the figure. These driving shafts could be coupled by a belt or transmission chain so that they would always turn at the same velocity, driven by a common motor. As explained in detail in Ref. 14, this "lateral" arrangement of the wheels allows rotation of the assembly around a vertical axis located between the driving shafts without necessitating discontinuous changes in the motor speed.

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. For example, consider the arrangement shown schematically in Fig. 4 where two assemblies are attached under a chassis. The constrained and unconstrained directions of each assembly are denoted by the letters c and u, respectively. If the platform needs to move in the x direction with the linear velocity Vx then the motor of assembly 1 needs to turn clockwise at a velocity $w = Vx/2\pi R$, R being the radius of the sliced ball wheels, while the motor of assembly 2 is not turning so that assembly 2 is only freewheeling during the motion. If the platform motion needed to be at a velocity V oriented at 45° from the x direction, then the motor of assembly 1 would need to turn at the velocity $w = (V/2\pi R)/\sqrt{2}$ (clockwise) and the motor of assembly 2 would need to turn at the velocity $-w$ (counterclockwise), while both assemblies would be freewheeling at velocity $V/\sqrt{2}$ in their respective unconstrained directions. Thus, by appropriately positioning several assemblies under a platform, it is possible to drive and control the platform in any direction while ensuring both load and directional stability. As shown in the next section, the system can also be given a rotational capability which can be controlled independently of the translational capability.

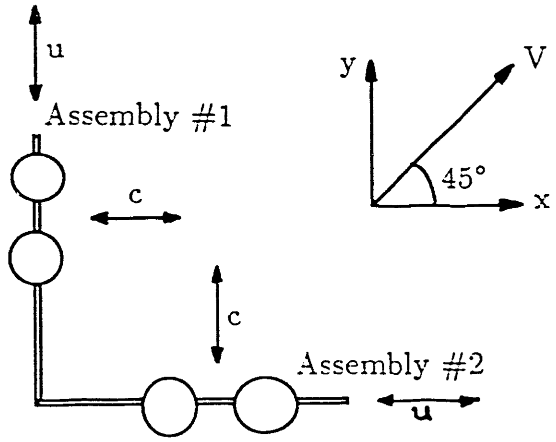


Fig. 4. Schematic of the constrained and unconstrained directions of motion for two orthogonal wheels assemblies.

III. PROTOTYPE PLATFORM DESIGN

Many options are available for positioning the wheel assemblies in the design of an omnidirectional mobile platform. 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 the assembly makes ground contact. The simplest layout involving three assemblies of the type shown in Fig. 2 was selected for the first platform prototype shown in Fig. 5. With the three assemblies oriented at 120° from each other, the platform stability is extremely easy to ensure. In addition, the $\frac{2\pi}{3}$ orientation relationship between the constrained motion directions provides excellent directional stability. Note that, without the benefit of a suspension system, a layout with four perpendicular assemblies would not provide added load stability and in some cases would invalidate the assurance of directional stability because of the possibility for non-contact of one of the wheels on uneven grounds. In the photograph shown in Fig. 5, the power supplies and the computer hardware mounted on the plexiglass deck of the platform have been removed to improve the viewing of the wheel assemblies' configuration. The computing hardware is composed of a seven slot VME bus with six slots occupied by a 68020 CPU, floppy controller, hard disk controller, serial ports, D/A, and A/D cards.

The control hardware consists of typical DC motors (visible in Fig. 5 near the center of the platform) controlled by the VME bus-based computer. Tachometers are included on the main shafts of the assemblies to provide feedback to the velocity control, and photosensors are used to track ground contact of the wheels. The photosensors can also act as crude encoders during large-scale motion by counting the wheel rotations. Figure 6 shows the basic control block diagram for one of the assemblies. The amplifier is set up in a velocity loop with feedback from the tachometer. 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.

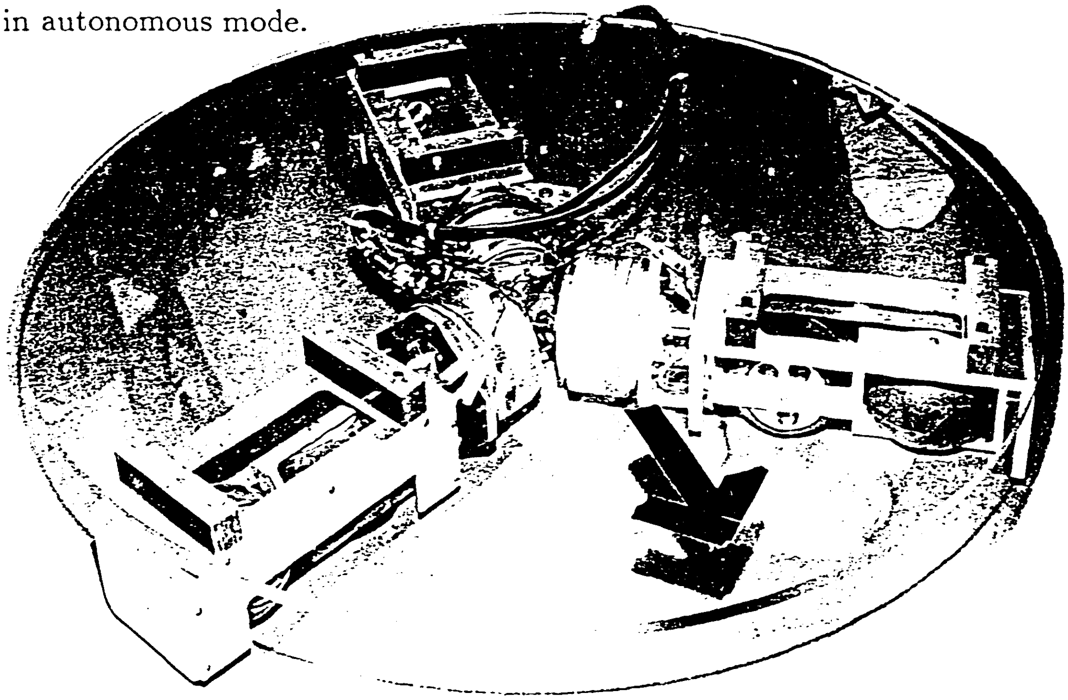


Fig. 5. Prototype platform using longitudinal orthogonal-wheel assemblies.

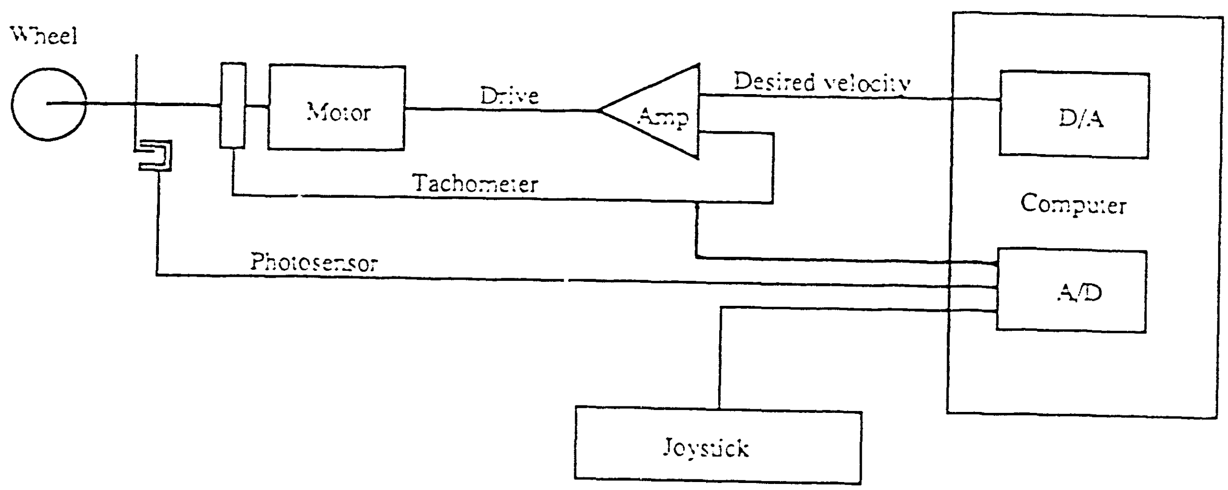


Fig. 6. Control block diagram of the orthogonal wheel prototype.

IV. KINEMATIC RELATIONSHIPS

Figure 7 shows the layout of the three orthogonal-wheels assemblies on the prototype platform. The constrained directions of motion of each assembly are indicated by the arrows labeled 1, 2, and 3. $\dot{\psi}$ denotes the angular velocity of the internal reference frame of the platform with respect to an absolute reference frame (x, y). The magnitude of the platform translational velocity is denoted by $|V|$ and its direction with respect to the platform internal reference frame is denoted by Θ. With these conventions, the driving shaft velocities, w_i, can be calculated as:

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

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

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

where D is the diameter of the ball 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) and (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. It is clear from these relations that the rotational and translational motions are fully decoupled and can be controlled independently and simultaneously. It is also clear that, although much simpler to implement for creating an omnidirectional capability in translation, the use of the "longitudinal" wheel assembly presents a challenge for the rotational capability of the platform since the control system has to approximate the step function in w_i due to the abrupt change in the values of L_i when contact switches from one wheel to the other. For fast rotating platforms, the "lateral" assembly mentioned previously would resolve this problem, and because of this advantage we have included it in the design of the second prototype.

In teleoperated mode, the signals from the joystick directly provide the values of $\dot{\psi}$, $|V|\sin\Theta$ and $|V|\cos\Theta$. The control system calculates the three shaft velocities from Eqs. (1), (2), and (3) 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" ($|V|$, Θ, $\dot{\psi}$) calculated by the reasoning systems at sensor sampling rate during sensor-based navigation. The inferencing modules for obstacle avoidance and decision-making in sensor-based navigation, which use the ring of twenty-four accoustic range sensors on the deck of the platform and a custom-designed VLSI fuzzy logic inferencing board, are described in detail in a companion paper.[15] In the user-provided trajectory following mode, the target configuration is compared to the current estimate of position and orientation calculated by the dead reckoning. The results provide the direction of motion and the platform target rotational and translational speeds using linear ramp up profiles, up to the pre-set maximum velocities. The corresponding shaft velocities w_{iest} are calculated from Eqs. (1) to (3) and are used to check that the maximum allowed shaft velocity is not exceeded. If this is the case, all velocities (the system in Eqs. (1) to (3) is linear) are decreased by the ratio $w_{iest}/w_{i\max}$ prior to being fed to the servo controls. Similarly, when the platform comes within a radius r_{slow} from its target location or within an angle ψ_{slow} from its target orientation, the calculated translational velocity $|V|$ or the rotational velocity $\dot{\psi}$ are decreased using linear ramp down profiles. When the location and rotation angle are both within given thresholds, r_{new} and ψ_{new}, from their target values, a new entry is read from the list and becomes the target configuration, or the platform stops if the list is exhausted.

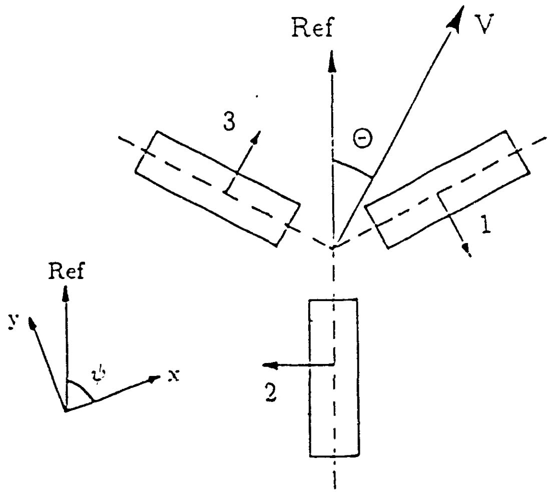


Fig. 7. Schematic of the orthogonal wheel assemblies layout for the prototype platform.

At each loop cycle (of length Δt), the dead reckoning system integrates the rotational and translational velocities to estimate the current orientation and position of the platform. Estimates of the platform motion parameters can be easily calculated from Eqs. (1) to (3) with the values of the shaft velocities w_i^* fedback during the loop cycle and the distance L_i obtained from the photosensors data:

$$\frac{\Delta\psi}{\Delta t} \approx \dot{\psi} = \frac{D(w_1^* + w_2^* + w_3^*)}{L_1 + L_2 + L_3} \tag{4}$$

and

$$|V|\sin\Theta = \pi D\left[\frac{(w_1^* + w_3^*)L_2 - w_2^*(L_1 + L_3)}{(L_1 + L_2 + L_3)}\right] \tag{5}$$

$$|V|\cos\Theta = \frac{\pi D}{\sqrt{3}}\left[\frac{-w_1^*(2L_3 + L_2) + w_2^*(L_1 - L_3) + w_3^*(2L_1 + L_2)}{L_1 + L_2 + L_3}\right] \tag{6}$$

If both right-hand sides (RHS) of Eqs. (5) and (6) are zero, then $|V| = 0$ and Θ is kept at its value from the previous loop cycle.

If only the RHS of Eq. (5) is zero, then $\Theta = 0$ or $\Theta = \pi$ depending on whether the sign of the RHS of Eq. (6) is positive or negative, respectively; and $|V|$ is given by Eq. (6). Similarly, if only the RHS of Eq. (6) is zero, then $\Theta = \pm\frac{\pi}{2}$ with the sign given by the sign of the RHS of Eq. (5), and $|V|$ is given by Eq. (5).

If neither RHS's are zero, then

$$\Theta = Artg\sqrt{3}\left[\frac{L_2(w_3^* + w_1^*) - w_2^*(L_3 + L_1)}{-w_1^*(2L_3 + L_2) + w_2^*(L_1 - L_3) + w_3^*(2L_1 + L_2)}\right], \text{ modulo } \pi, \tag{7}$$

with Θ determined by the sign of the RHS of Eq. (5), and $|V|$ given by Eq. (5) or Eq. (6).

The implementation of the dead reckoning at 100 Hz provided very acceptable results for translational motions as discussed in the next section. Some errors were observed as expected during fast rotational motions which, as mentioned previously, are due more to the use of the longitudinal assembly design than to the dead reckoning integration scheme.

V. EXPERIMENTAL RESULTS

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 platform control system. Figure 8 shows the platform during one of these tests made to illustrate the translational omnidirectionality of the platform. 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 3 cm for this trajectory which was about 6 m in length, indicating the very good accuracy of the dead reckoning system in translational motions. In repeated experiments with this and other trajectories, the error during translational motions was found systematically less than 1% of the length of the trajectory.

Figure 9 shows a sequence of pictures which illustrate the platform capability for simultaneous motions in translation and rotation. A small triangular flag has been added on the platform to display its "spinning" motion while it translates along a straight line. As indicated by Eqs. (1) to (3) the demand on the rotational and translational velocities of the platform are fully decoupled and independent. As expected, the accuracy of the dead reckoning system for the rotational component of the motions was found much worse than that for the translational motions, with typical errors reaching 10% of the total rotation for fast (near the motor limits) rotational motions. As discussed previously, detection of the exact time at which ground contact switches from one ball to the other in the assembly is critical, and with the 100 Hz loop rate utilized here, the $\pm$ .01s approximations of these switch times lead to random errors which can accumulate to significant magnitudes. The "lateral" orthogonal-wheels assembly described in the previous sections was designed to remedy this problem for rotational motions and will serve as the basic assembly for our second test-bed platform. Because of its easily constructed drive-train, however, the "longitudinal" assembly may remain the design of choice for omnidirectional platforms which do not require fast rotational motion capabilities.

The very important characteristic of mobile platforms based on orthogonal-wheels assemblies is their overall holonomy: no constraints exist on the platform velocity direction. Coupled with the omnidirectional capability, this gives full dimension to the space of achievable configurations and velocities, a characteristic not achieved with any of the conventional wheeled platforms. This feature is particularly interesting for the design of large, possibly odd-shaped robotic platforms or vehicles. The basic platforms discussed in this paper can be viewed as omnidirectional, holonomic, fully controllable, and statically stable "casters." Proper coordinated control of several of these low profile (small wheel well) casters underneath a large platform would in turn provide full holonomy and omnidirectionality to that platform.

VI. CONCLUDING REMARKS

An original orthogonal-wheels assembly concept which exhibits constrained and unconstrained directions of motion has been presented. Two possible configurations of the wheels in the basic assembly have been discussed and their use in producing omnidirectionality of a platform by combining the constrained motions of several assemblies has been described. A design has been proposed to produce fully holonomic platforms, i.e., platforms with simultaneous, independent, and unconstrained rotational and translational motions. A prototype of such a platform has been constructed using three "longitudinal" orthogonal-wheels assemblies and its control system has been described. Proof-of-principle experiments illustrating the orthogonal-wheels assembly concept and the platform omnidirectionality with simultaneous and independent translational and rotational motions have been presented. Data from the experiments with this first prototype suggest that very accurate control of the omnidirectional translation motions can be obtained using "longitudinal" orthogonal-wheels assemblies, and that significant improvements in the control of the platform rotational motions could be realized using a "lateral" type of orthogonal-wheels assemblies at the cost of a slight additional complexity in the design of the drive trains. Our on-going work focuses on the design and comparative testing of a second platform prototype utilizing this lateral type of assembly.

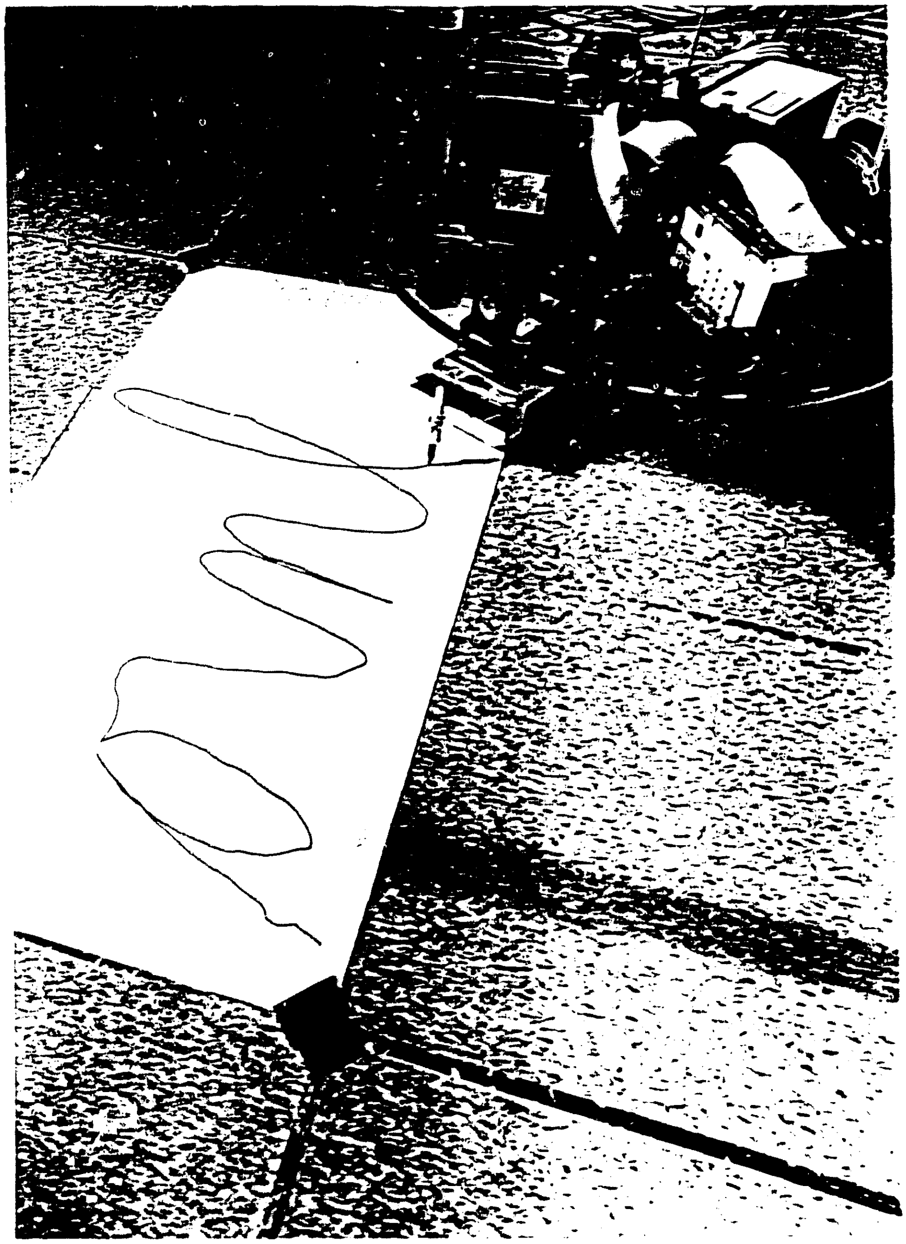
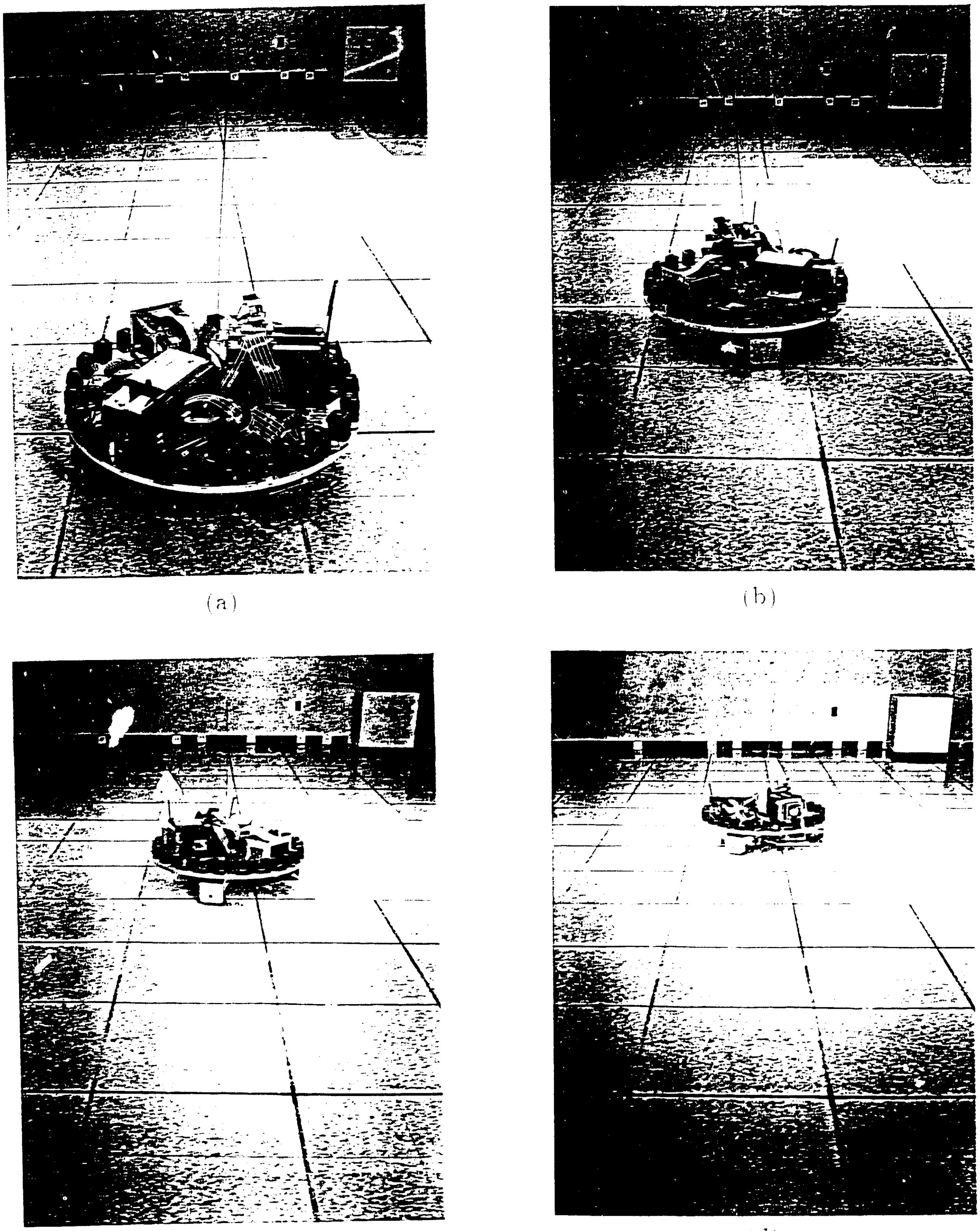


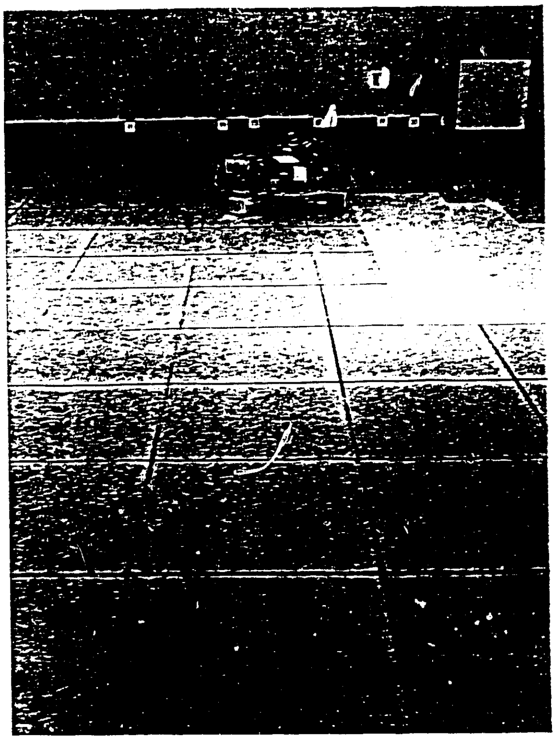
Fig. 8. Platform performing a trajectory requiring translational omnidirectionality.



(a) (b)

(c) (d)

Fig. 9. Sequence of pictures illustrating the simultaneous rotation and translation capability of the platform.



(e)

Fig. 9 (cont'd).

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