CONTROL OF AN ONMI-DIRECTIONAL ROBOTIC VEHICLE WITH MECANUM WHEELS

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Abstract

Mecanum wheels, referring to the name of the original Swedish manufacturer, have rollers as treads. The roller have axles skewed with respect to the wheel axle. These wheels provide a practical way of providing simultaneous vehicle motion in all three directions, longitudinal, lateral, and yaw, without singularities. (All vehicles using conventional wheels or tracks must make large propulsion system motions in order to execute most arbitrarily small moves, thus they are singular.) This paper explores three aspects of the Mecanum wheeled vehicles, the ability to maneuver in congested spaces, the kinematics of wheel design, and considerations for wheel loading and traction. It is shown how omni-directional capability greatly reduces the amount of area and time required for maneuvers, and how the Mecanum wheel in particular reduces time because of the absence of singularities. The algorithms to convert desired motions to required wheel motions do not require excessive computation even in the case where they include compensation for wheel slip detection and correction.

Introduction

This paper discusses the Mecanum wheel as a component in robotic vehicle propulsion. The strength of this wheel is the enhanced maneuverability of the vehicle -- the vehicle can proceed in any direction without the slipping or delay associated with conventional wheel or track drives. Any direction means any combination of translation, lateral, and rotary motion. The order of presentation is: uniqueness of the Mecanum wheel for motion in all directions, in particular the non-singular characteristics; the savings in space and time relative steered and omni directional schemes using conventional wheels; some fundamental relationships that describe the wheel design; and some considerations in achieving high traction and operation in loose soil.

The Mecanum Wheel

A multi-directional vehicle (MDV) is one that can move independently and simultaneously in all three possible directions of motion; longitudinal (forward/reverse), lateral (right/left), and rotary. Thus the control system must have at least 3 degrees-of-freedom (DOF).

Conventionally steered vehicles, such as automobiles, bicycles, and most industrial vehicles, etc., have only two DOF (longitudinal and steering). Often in these conventional cases the longitudinal motion is directly controlled by a propulsion/brake system. A single steering angle is controlled which couples the longitudinal motion to the lateral and rotary motion of the vehicle.

Here we consider the Mecanum wheel (a wheel with rollers for treads). Figure 1 shows an example of this wheel.

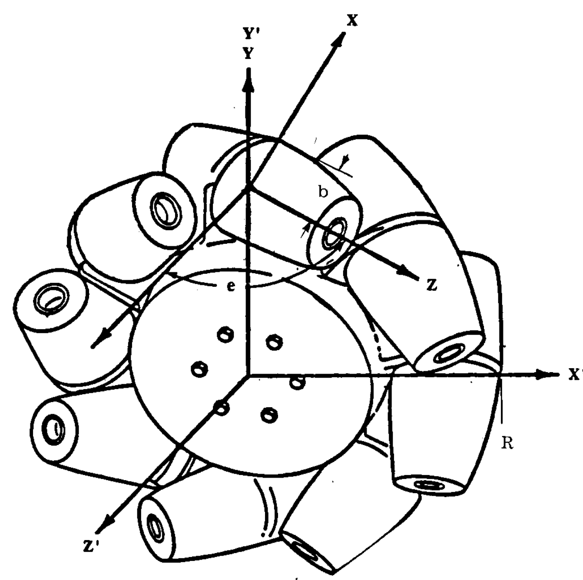

Figure 1. A Mecanum Wheel with Coordinate Systems.

A vehicle using these wheels may have 4 wheels arranged in a rectangular pattern as shown in Figure 2.

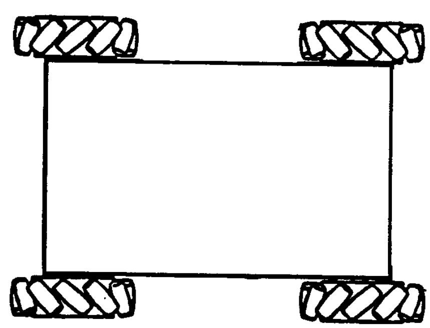

Figure 2. Wheel Configuration - Bottom View.

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All of the wheels are independently powered. In the case of vehicles with conventional wheels all of the wheels must be independently steerable in order to have the ability to move in an arbitrary direction on a surface and at least two wheels must be independently powered. Before going further, it would be beneficial to remind the reader that there are many possible variations in wheel patterns, that are not explicitly considered here. Some of the more interesting are:

1. Use of three wheels. Since three points define a plane, this results in the load on the wheels being distributed by Newton's laws only. The suspension and/or wheels need no compliance to remain in contact with a floor that is smooth (but not necessarily flat). These vehicles are easier to tip over.

2. Addition of castor wheels. Any number of undriven wheels that are free to follow the path of the vehicle can be added to distribute weight and/or add stability. This reduces traction but may simplify the design of a vehicle.

The Mecanum wheel can be thought of as a conventional cylindrical wheel with unusual treads. The treads in this case are themselves rollers. At any instant of time, each roller has a curved line on its surface that is also on the surface of the cylinder (as is a conventional tread). All other points of the roller are interior to the cylinder describing the wheel. In order that any propulsive effort be exerted by rotating the wheel these rollers must be mounted at an angle with respect to the axis of the wheel. In addition, as with a conventional tread, at least one point on one roller must be directly below the axis of the wheel in order to avoid an up and down motion as successive rollers, or treads, come in contact. This feature also requires the rollers to be at an angle.

Non-Singular Non-sliding Motion

It is generally recognized that omni-directional propulsion is a desirable trait of very maneuverable vehicles. Such vehicles are called multi-directional vehicles, MDV, here. However, less well recognized is that most schemes for such propulsion are inherently singular AND require slipping of the wheels or tracks. Singularity means that a small motion in some directions may require a large motion of the propulsion system. Consider for example, the case of a vehicle with four independently driven and steered wheels. This is called an all-wheel steered vehicle here. Such a vehicle, can proceed in any direction, including a simultaneous yaw by aligning the wheels properly. However, if the vehicle is to proceed in a direction (a 3 element vector) different than the current direction, even for an infinitesimal distance, the wheel orientations may need to be changed dramatically. This characteristic would not be tolerated in most motion control systems, for example machine tools and robots, however, by tradition most vehicles have that characteristic, resulting in delays and in fact the inability to make small precise motions.

Space and Time Considerations

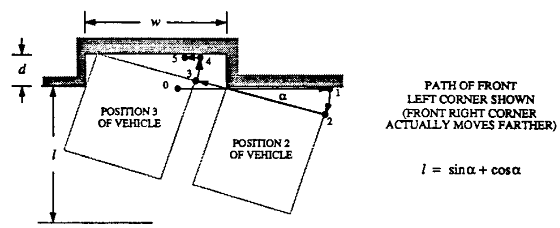
An advantage of an MDV over a conventional vehicle is the reduction of floor space required for various maneuvers. There is also a reduction in the length of travel required to accomplish many maneuvers. In order to illustrate this two common maneuvers are considered, docking and turning a corner. In both cases, we will consider a vehicle of unit length and unit width. Floor space requirements for different lengths scale with the length squared.

In every case a plus and minus 90 degree turning angle capability is assumed for the conventionally steered vehicle although many such vehicles have more limited steering angles. With a 90 degree steering angle the steered wheels must be powered.

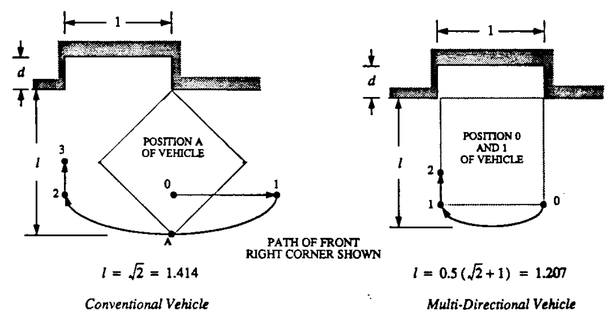
One of the most important features of a vehicle with Mecanum wheels relative to an all wheel steered vehicle is that the former can move a small amount in any direction without a large motion of the wheels. That is, small vehicle motions require small wheel motions. An all wheel steered vehicle in the parlance of robotics is "singular" in all operating conditions. That is, in order to make an arbitrarily small motion the four wheels may need to be turned up to 90 degrees. This makes motion times longer for an all wheel steered vehicle relative to the Mecanum wheeled vehicle even though both are MDV's.

Docking (parallel and perpendicular parking):

Two docking maneuvers are considered as illustrated in Figure 3.



a) Parallel Docking (Conventional Vehicle)



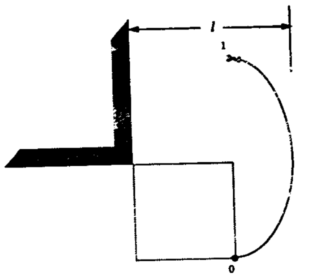
b) Perpendicular Docking

Figure 3. Docking Maneuvers.

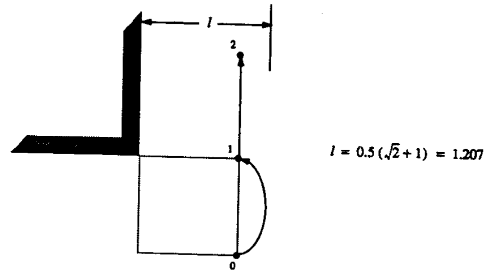
In one case the vehicle must dock parallel to the original direction of motion. In the other it must dock perpendicular to the original direction of motion. The original motion is assumed to be along a wall so that in docking no infringement of that wall is allowed. Figure 3 shows the assumed motions for both the MDV case and the conventional case. The MDV parallel docking case is so trivial (move sideways) that it is not illustrated.

Turning a Corner:

For some tasks, an MDV might handle a corner much differently than a conventional vehicle. That is, rather than turn, the vehicle could move sideways for a distance similar to the parallel docking maneuver. In many cases this would reduce the time as well as the space requirements. However, here assume a corner is to be turned, and again use the unit length and width vehicle. Figure 4 illustrates a 90 degree turn for both the MDV and conventional cases.



a) *Conventional*



b) *Multi-Directional*

Figure 4. Turning a Corner.

AREA:

		Parallel Dock	Perpendicular Dock	Right Turn
Multi-directional vehicle		$d + 1$	$L + d$	$L(1 + L)$.
Conventional vehicle		$(d + L)(w + 1)$	$2(L + d)$	$2L$
Ratio*	d = 0.1	218%	232%	106%
	d = 0.3	248%	227%	106%
	d = 0.6	291%	223%	106%

PATH LENGTH:

		Parallel Dock	Perpendicular Dock	Right Turn
Multi-directional vehicle		d	$1.207 + d$	2.111
Conventional vehicle		$2\alpha + 2w - 1 + \frac{1}{\cos(\alpha)}$ where $\tan(\alpha) = d$ and $w = d^2 + 1$	$3.221 + d$	2.221
Ratio*	d = 0.1	2224%	254%	105%
	d = 0.3	936%	234%	105%
	d = 0.6	661%	234%	105%

SINGULAR MOVES:

	Parallel Dock	Perpendicular Dock	Right Turn
Omni-directional vehicle	0	0	0
All-wheel vehicle	1	2	2
Conventional vehicle	4	2	2

* Ratio is CONVENTIONAL to MDV

Table 1. Area, Path Length, and Singular Moves for Docking and Turning.

Results:

Measures of area, path length and number of singular maneuvers for conventional and MDV vehicles are given in Table 1.

If the MDV has Mecanum wheels, it has no singular motions. Again a large advantage is seen for the MDV, particularly with Mecanum wheels. The path length has been taken as the length travelled by that wheel that moves the furthest. Because these calculations are done for a unit length vehicle, distances scale with vehicle length and areas scale with vehicle length squared.

The particular maneuvers shown in Figures 3 and 4 are not necessarily optimal for all situations. They are intended to be reasonable for comparisons between the various vehicle configurations. In particular, a steered wheel vehicle would probably use rounded trajectories to avoid the sudden changes in direction, because a steered vehicle loses time in making a sudden change in direction.

Notice for the cases considered, the conventional vehicle requires at least twice the floor space and twice the path length for both type of docking maneuvers relative to an MDV. Furthermore, of the two types of MDV's, the Mecanum wheeled vehicle has no "singular" moves while a steered vehicle does. The importance of the non-singular characteristic of an ODV cannot be overstated. A real docking maneuver (or other maneuver) rarely can be made in the ideal way illustrated. Rather, constant corrections in the trajectory must be made. Each correction is likely to require a singular motion. The ODV is superior in making these corrections because of its non-singular motion characteristics.

Fundamental Kinematics

The geometry of the rollers in a Mecanuum wheel is a function of wheel radius, R; maximum roller radius, b; and roller angle, e as illustrated in Figure 1. It is convenient in all of the following discussion to make R = 1, which simply normalizes the problem. Thus b is unitless and is the ration of b to R if units are used. The roller geometry is described by its radius, r, as a function of the distance, z_1, from the center of the roller as follows:

$$\begin{aligned} r &= \sqrt{(x_1^2 + y_1^2)} \\ z_1 &= z\,(c*\sin^2(e) + \cos^2(e)) \\ \text{where } x_1 &= (c-1)*z*\sin(e)*\cos(e) \qquad (1) \\ y_1 &= (c-1)\,(1-b) \\ \text{and} \quad c &= \left(\sqrt{[(1-b)^2 + z^2*\sin^2(e)]}\right)^{-1} \end{aligned}$$

The derivation of these equations is not published here. This set of equations seem to be simpler than given previously. The quantity z is used to generate the shape. In interpreting these equations, the point (x_1, y_1, z_1) is a point on the roller surface which is also on the wheel surface. This can be thought of as a point on the "tread" spoken of earlier. The points are in the roller coordinate system with original in the middle of the roller, the z-axis coincident with the roller axis, and y-axis perpendicular to the wheel surface, not the roller surface as shown in Figure 1. The generating value, z, on the roller axis, is <u>also</u> on the normal to the wheel at the point (x_1, y_1, z_1). The final result is r as a function of z, which completely describes the roller geometry.

If b and e have been chosen, the wheel geometry is governed by two primary considerations. First there must be some minimum clearance between rollers. This sets the minimum number of evenly spaced rollers. Second, to avoid gaps between rollers in contact with the floor, the length of the rollers must be great enough so that at least one point of one roller must be on the wheel circumference at every angle of the wheel. If this were not done the roller would "bump" between rollers.

The assumption made here to calculate the maximum number of rollers is that two adjacent rollers are closest together on the plane containing the center of the wheel and perpendicular to the wheel axis. The roller defines an elliptical like area on this plane. There is an angle, Θ, which can be determined numerically for any value of b, and e. Θ is the angle that bounds this elliptical area. Thus,

$$N = \frac{360}{\Theta} \qquad (2)$$

is the maximum number of rollers in a wheel. Because this number is generally not an integer, the integer part is the actual maximum number of rollers. The fractional part of N represents clearance between rollers, taken as a group.

The requirement that at least one point on one roller is to be on the floor directly below the axis, results in a minimum length of a roller and a minimum width of the wheel (defined by the ends of the roller axis). The minimum length of the roller can be calculated by requiring that each roller span a minimum angle, ϕ.

$$\phi = \frac{360*\text{overlap}}{\text{integer (N)}} \qquad (3)$$

An "overlap" of 1 means that exactly one roller is in contact for any position of the wheel. An "overlap" between 1 and 2 means that at some wheel positions, two rollers will be in contact at the same time. To minimize wear and maximize controllability an overlap of 1 is desirable. This results in a single point of contact with no "bumping" from roller to roller. Any design must meet the additional constraint that the minimum roller diameter be greater than 0. This results in an absolute maximum roller length given by

$$\text{max.roller.length} = \frac{2\sqrt{b(2-b)}}{\sin(e)} \qquad (4)$$

This in turn leads to an absolute maximum wheel width of

$$\text{max.wheel.width} = \text{max.roller.length}*\cos(e) \qquad (5)$$

In these two equations R = 1 is assumed. The formulas are a direct result of taking c = 1 in Equation 1 above.

A computer program was written to calculate the roller geometry for any value of e and b. It also calculates the number of rollers that can be used in a wheel for any e and b. If the overlap is supplied, it calculates the width of the wheel. Table 2 is the result of these calculations for e = 45 degrees and an overlap of one.

ROLLER CHARACTERISTICS			
Max Rad.	Min Rad.	Whl Width	No. of
0.10000	0.08824	0.29898	20.53953
0.10500	0.09200	0.31394	19.48096
0.11000	0.09554	0.33058	18.51860
0.11500	0.09883	0.34918	17.63984
0.12000	0.10178	0.37013	16.83410
0.12500	0.10683	0.36914	16.09274
0.13000	0.10936	0.39284	15.40834
0.13500	0.11135	0.41995	14.77453
0.14000	0.11642	0.41881	14.18590
0.14500	0.11769	0.45005	13.63776
0.15000	0.12276	0.44882	13.12602
0.15500	0.12308	0.48524	12.64719
0.16000	0.12817	0.48390	12.19823
0.16500	0.12715	0.52691	11.77631
0.17000	0.13225	0.52544	11.37913
0.17500	0.13736	0.52397	11.00451
0.18000	0.13447	0.57545	10.65060
0.18500	0.13960	0.57383	10.31568
0.19000	0.13392	0.63684	9.99826
0.19500	0.13908	0.63502	9.69700
0.20000	0.14424	0.63320	9.41067
0.20500	0.14941	0.63138	9.13818
0.21000	0.13950	0.70991	8.87853
0.21500	0.14471	0.70784	8.63081
0.22000	0.14992	0.70577	8.39420
0.22500	0.15513	0.70370	8.16798
0.23000	0.13835	0.80470	7.95142
0.23500	0.14364	0.80229	7.74393
0.24000	0.14892	0.79988	7.54493
0.24500	0.15420	0.79747	7.35388
0.25000	0.15948	0.79506	7.17031
0.25500	0.13072	0.93013	6.99376
0.26000	0.13612	0.92724	6.82382
0.26500	0.14152	0.92435	6.66012
0.27000	0.14692	0.92147	6.50228
0.27500	0.15232	0.91858	6.34999
0.28000	0.15773	0.91569	6.20293
0.28500	0.16313	0.91281	6.06082
0.29000	0.11132	1.10363	5.92340
0.29500	0.11694	1.10000	5.79041
0.30000	0.12256	1.09637	5.66162
0.30500	0.12818	1.09273	5.53680
0.31000	0.13380	1.08910	5.41577
0.31500	0.13943	1.08547	5.29832
0.32000	0.14505	1.08183	5.18426
0.32500	0.15067	1.07820	5.07343
0.33000	0.04545	1.37711	4.96567
0.33500	0.05157	1.37211	4.86082
0.34000	0.05769	1.36711	4.75873
0.34500	0.06382	1.36211	4.65926
0.35000	0.06994	1.35711	4.56228
0.35500	0.07606	1.35211	4.46767
0.36000	0.08219	1.34711	4.37529
0.36500	0.08831	1.34211	4.28504
0.37000	0.09444	1.33711	4.19680
0.37500	0.10056	1.33211	4.11046
0.38000	0.10668	1.32711	4.02590
0.38500	-0.18183	(must end	

Table 2. Wheel Characteristics for Varying Roller Diameters.

Recall that the number of rollers is actually the integer value in the "number of rollers" column. The fractional part of the number of rollers represents the space occupied by the clearance between wheels. For example, if the number of wheels is given as 5.4, then there are 5 rollers, and all 5 clearances taken together occupies the space of 40% of one roller.

The table also contains other information. One item of interest is the minimum radius of the roller. This is the radius at the small end of the roller. The most immediate implications of the table are that the minimum number of rollers is 4. Less obvious is that if one wants to maximize the minimum roller radius the number of rollers is 6. The actual required length of the rollers, and hence the minimum roller radius, is determined by the condition in Equation 3 for the angle, ϕ. For Mecanum wheels with multiple rows of rollers, each roller can occupy a lesser angle, the angle for a single row of rollers divided by the number of rows. This leads to larger rollers and hence less "floor loading" as discussed below.

Traction and Loading Considerations

An ideal hard Mecanum wheel on a hard surface has point contact. A conventional wheel has line contact. In either case, the floor or wheel must deflect to have finite contact pressure. However there is concern that the Mecanum wheel leads to higher contact pressure because of its theoretical point contact. The concern is that either the wheel or surface on which the vehicle is operating could be damaged. A second concern with these wheels is a presumed lack of traction because the wheels offer no resistance in the direction perpendicular to the roller axes. The following comments are addressed to these concerns.

Contact pressure is primarily undesirable because it leads to "wear" of the wheel or floor surface. However, for a vehicle that maneuvers aggressively, the conventional wheeled vehicle experiences considerable scuffing on the floor as the wheel is turned. This sliding is also a source of wear, and may in many situations be a more important determinant of wear (as well as power consumption). The Mecanum wheel does not slip when moving in any direction, however, as with any wheel there is some scuffing that results from the deflection of the materials as the wheel rolls.

In addition, surface contact pressure can be minimized by using relatively few rollers; 6 is the optimal for a single row of rollers as can be determined from Table 2. It was pointed out earlier that theoretically, two or more rolls of rollers can be used while s till maintaining only the single "point" of contact needed to prevent sliding, and reduce the contact pressure even more. No application of this principle is known to the authors. However, Figure 5 illustrates such a wheel.

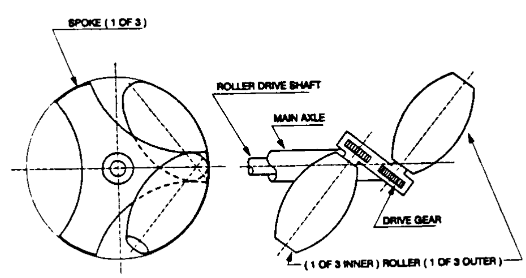


Figure 5. Modified Wheel for Higher Traction and Lower Contact Pressure.

Traction is another interesting case, with interesting solutions if traction is an overwhelming requirement. First, the Mecanum wheel actually does result in less frictional traction for a vehicle that is stationary. It is easy to verify that with 45 degree roller angles, static friction in the direction of a roller axis is zero and therefore, in such a direction, the static friction is typically 50% of the case for a wheeled vehicle, with all wheels locked. In a moving case, two effects must be weighed against this degradation. First, the wheeled vehicle must have all wheels driven, if only two are driven, the static traction is typically the same 50%. Second, during a maneuver of a conventional vehicle, where wheel direction is changing, either to change direction, or to compensate for slipping, the wheels will be sliding, which itself reduces friction.

Nothing, except cost, prevents the rollers of a Mecanum wheel from being powered. This has not been done to the author's knowledge, but does bring the Mecanum wheel back to the same static friction traction as a conventional wheeled system. See Figure 5 again.

Furthermore, the Mecanum wheel can act as a very aggressive tread, in those cases where a vehicle is to be operated in mud or sand. In extreme cases, the rollers can be locked and the vehicle operated as a conventional four wheel drive vehicle. This eliminates the omni-directional capability but does provide excellent traction. Finally, if the wheels have sunk into mud or sand the wheels can be operated as screws. This maintains the omni directional capability, but completely changes the equations of motion.

Conclusions

This paper argues that the Mecanum wheel is potentially valuable for vehicles that need extreme maneuverability in battlefield situations as well as in other applications. As far as the authors know, no other wheeled contact system of propulsion provides the non-singular motion characteristics needed to make rapid changes in direction of motion needed for those situations requiring aggressive maneuvering.

The paper also presents some novel concepts, the multiple row driven wheel and the screw type variation of the Mecanum wheel, as well as a simple wheel design formulation, Equation 1.

Acknowledgements

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