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Design, Modeling and Control of an Omni-directional Mobile Robot

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Abstract. One of the main issues of a mobile robot is to move in tight areas, to avoid obstacles, finding its way to the next location. These capabilities mainly depend on the wheels design. An omni-directional drive mechanism is very attractive because it guarantees a very good mobility in such cases. This paper provides some information about the mechanical design of an omni-directional robot, as well as about its control. This report is the result of the cooperation between researchers from Mechanical Engineering and Electrical Engineering Faculties, at "Gh. Asachi" Technical University of Iasi, Romania.

Introduction

Mobility is one of the main issues of a mobile robot when it has to move in small and narrow spaces and to avoid obstacles. An omni-directional drive mechanism is very attractive because it guarantees a very good mobility in such cases. This capability mainly depends on the wheels design. Among many types of omni-directional wheels, Mecanum wheels are widely used in several applications, when a very good mobility of the robot is required.

A Mecanum omni-directional wheel consists of one active main hub and several free moving rollers angled at 45° about the hub's circumference. The angle between rollers axis and central wheel axis could have any value but in the case of conventional Mecanum wheel it is 45˚. The wheel has 3 DOFs composed of wheel rotation, roller rotation, and rotational slip about the vertical axis passing through the point of contact.

Using four of these wheels provides omni-directional movement for a vehicle without needing a conventional steering system [1-3]. The benefits of a vehicle with Mecanum wheels relative to one with steered wheels have been presented by [2]. In the omni-directional wheel, its velocity can be divided into the components in the active direction and in the passive direction. The active component is directed along the axis of the roller in contact with the ground, while the passive one is perpendicular to the roller axis. When the wheel rotates, a force vector along the wheel and a force vector perpendicular to the wheel are created. Depending on each individual wheel direction and speed, the resulting combination of all these forces produce a total force vector in any desired direction thus allowing the platform to move freely in the direction of the resulting force vector, without steering them. By a simple control of each wheel rotation, the robot moving direction can be changed instantaneously. [4] and [5] introduced the kinematics of Uranus robot and developed an algorithm for feedback control of it. Many other projects with four Mecanum wheels have been presented by [6], [7].

This paper introduces a mobile robot with omni-directional motion capabilities, thanks to its Mecanum wheels. It provides some information about the mechanical design of the wheel and robot, about their kinematics, as well as about its electronics and control strategies. This report is the result of a research conducted at the "Gh. Asachi" Technical University of Iasi, Theory of Mechanisms and Robotics Department.

Wheel Design

The rollers are shaped such that the silhouette of the omni-directional wheel is circular (Fig. 1). The shape of each roller is such that its surface never protrudes outside the surface of an imaginary cylinder that represents the outer surface of an ordinary wheel. We can get the shape of a roller if we cat the imaginary cylinder, having as diameter the external diameter of the wheel, by a plane angled at γ (the angle between roller and hub axes), in our case $\gamma = 45^{\circ}$ (see Fig. 2). Since the axis of rotation is offset by some angle to the axis of the wheel, there is a finite length that each roller can be, depending on the distance of the rollers from the wheels centre (Fig. 3). If this angle of offset is γ then the profile of the side of the roller is the arc of an ellipse, whose secondary axis is the radius of the wheel, R, and whose primary axis is $1/\sin\gamma$ times the radius of the wheel. The roller shape should respect the equation:

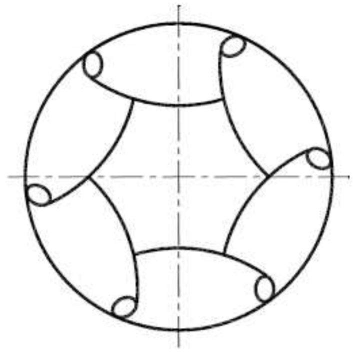

Fig. 1 Wheel silhouette

$$\frac{x^2}{(R/\sin\gamma)^2} + \frac{y^2}{R^2} = 1. \quad (1)$$

Depending of the length of the roller, L_r and the wheel radius, R, the shape of the roller can be approximated with a circle.

In order to get a circular silhouette for the wheel (see Fig. 1), a minimum number of rollers should be chosen (Fig. 3). The number of rollers per wheel is dependent upon the size of each roller, which is a function of how close we design the roller axis of rotation to the center of the wheel. The closer the axis of rotation, the longer each roller can be, and so less is needed to span the circumferential area of the wheel.

If the external wheel radius, R, the maximum radius of a roller, $r_{\max}$ $r_{\max}$ and the rollers number, n, are known ($n = 2\pi/\varphi$), then the roller length, L_r can be derived as

$$L_r = \frac{2\cdot(R - r_{\max})\cdot\tan\frac{\varphi}{2}}{\sin\gamma} = \frac{2\cdot(R - r_{\max})\cdot\tan\frac{\pi}{n}}{\sin\gamma}. \quad (2)$$

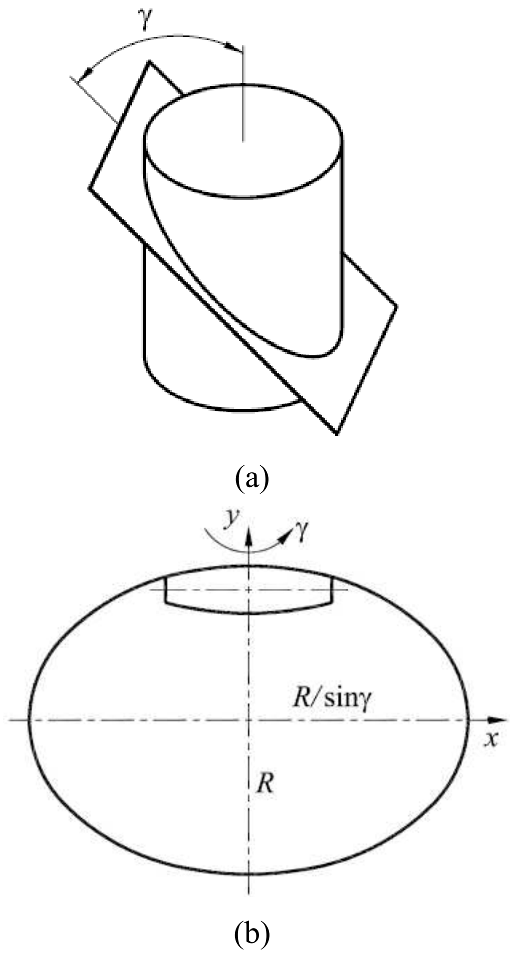

Fig. 2 Roller shape

The size of the rollers also has an effect upon performance of the wheel on a variety of surfaces. Consider a basic step change in surface being ascended by a wheel of this type. The height of step change that the wheel can successfully overcome is a function of the roller minimum diameter. The larger the rollers are the greater the range of surface deviations that can be overcome. Also as the size of the rollers increases, the slower they spin, resulting in lower friction losses in the driving of the wheel. In summary, when designing a new drive system for a robot of this kind, there exist a certain number of rollers that makes the ideal compromise between having a small number of large rollers per wheel, and having a large number of small rollers per wheel.

Having the roller length, L_r we can get the minimum radius of the roller, $r_{\min}$ to its extremities:

$$r_{\min} = \frac{-A + \sqrt{A^2 - 4B}}{2A}, \tag{3}$$

where

$$A = 2 \cdot (R - r_{\max}) \tag{4}$$

$$B = \left(\frac{R - r_{\max}}{\cos\frac{\varphi}{2}} \right)^2 - R^2 = \left(\frac{R - r_{\max}}{\cos\frac{\pi}{n}} \right)^2 - R^2. \tag{5}$$

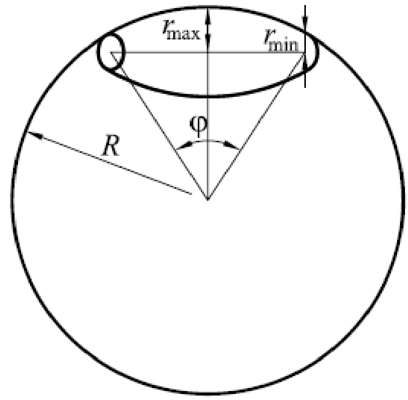

Fig. 3 Roller size

Large size of rollers means a small number of them. But this has as effect a very small radius $r_{\min}$ to the rollers extremities (see Fig. 1). In this case, it could be difficult to use ball bearings, in order to decrease the friction between roller and its axis. To eliminate this problem, a new constructive solution of Mecanum wheel is proposed (Fig. 4). This solution not only facilitate the use of big bearings but also make possible the approximation of the roller shape with a circle (the roller length becomes smaller than the one used in a classical Mecanum wheel – it is half of the normal roller).

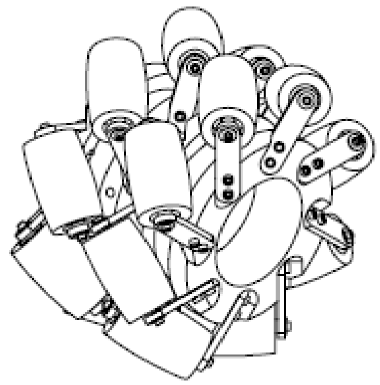

Fig. 4 New wheel design

Wheel kinematics

When a Mecanum wheel is rotating, at least one roller (maximum two rollers) is (are) in contact with the ground. Only a small surface (theoretical, one point) of the roller is in contact with the ground. The area of this surface traverses the roller from one side to another, depending on the sense of wheel rotation. The direction of the traction force will be done by the traversing sense of contact surface. It means, if we look to the wheel from the top side, the traction force will be perpendicular to the roller axis (Fig. 5). Starting from this description, the effective rotational velocity of the Mecanum wheel will not be that of a standard wheel ($\omega_w = i \cdot \omega_m$, where i is the gear ratio and ω_m is the rotational velocity of the driving motor) but:

$$\omega_w = i \cdot \omega_m \cdot \sin\gamma. \tag{6}$$

This rotational velocity could also be found from encoder pulses,

$$\omega_w = k \cdot \frac{\Delta N}{\Delta T}. \tag{7}$$

where: k is a constant depending on the number of pulses per encoder revolution, the radius of Mecanum wheel and the gear ratio, i; ΔN is the change of encoder pulses; ΔT is the time interval of sampling encoder pulses.

From Eq. 6, we can see that when rollers are mounted with their axes parallel to the wheel axis, negligible motion will be achieved because the roller in contact with the ground will only produces wheel slip. When the rollers are mounted perpendicular to the wheel axis, a maximum motion will be produced and the rotational velocity of the wheel will be $\omega_w = i \cdot \omega_m$. The wheel slip is mainly caused by rollers rotation around their axes when the wheel is rotating:

$$s = \frac{d_r}{d_t} = \frac{d_r}{\omega_w \cdot R \cdot \Delta T} = \frac{d_r}{i \cdot \omega_m \cdot R \cdot \Delta T \cdot \sin\gamma}, \tag{8}$$

where d_r is the real displacement produced by a Mecanum wheel rotation and d_t is the computed displacement produced by the same wheel.

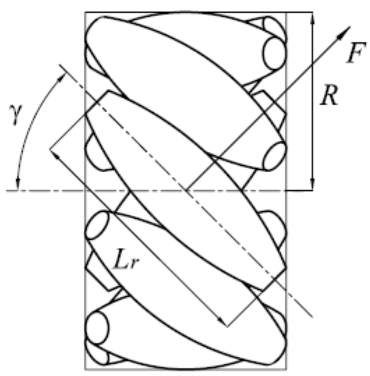

Fig. 5 Top side of the wheel

Experimental Platform

Our actual four-wheel mobile robot has a rectangular shape with the four Mecanum wheels supporting the robot (Fig. 6). It consists of four mine parts: mobile base (including four Mecanum wheels, four geared brushless AC motors, four suspension sets and batteries), driving control box (including four servo-amplifiers and a Motorola phyCORE-mpc555 module), a laptop and a FF380 Force Feedback Race Master as interface to the human operator.

When Mecanum wheels are actuated, the angled peripheral rollers translate a portion of the force in the rotational direction of the wheel to a force normal to the wheel direction. Depending on each individual wheel direction and velocity, the resulting combination of all these forces produce a total force vector in any desired direction thus allowing the platform to move freely in the direction of the resulting force vector, without changing of the wheels themselves.

The mobile robot is under velocity control. Given the Cartesian space velocity, the velocity of each motor is computed by using the inverse Jacobian:

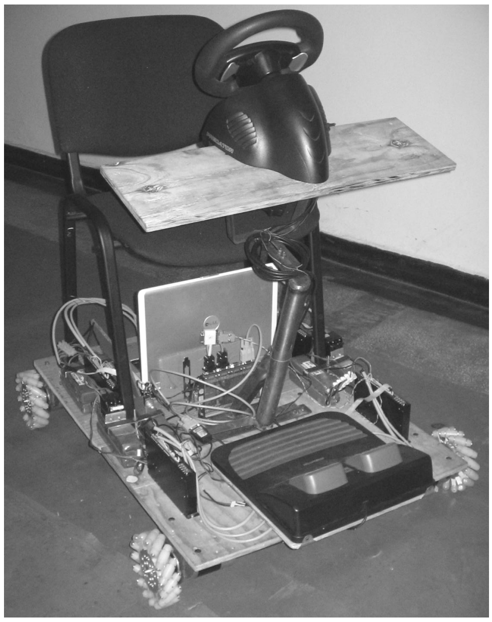
Fig. 6 Experimental platform

$$\begin{bmatrix} \omega_1(t) \\ \omega_2(t) \\ \omega_3(t) \\ \omega_4(t) \end{bmatrix} = \frac{1}{R} \begin{bmatrix} 1 & 1 & -(l_1+l_2) \\ -1 & 1 & l_1+l_2 \\ -1 & 1 & -(l_1+l_2) \\ 1 & 1 & l_1+l_2 \end{bmatrix} \cdot \begin{bmatrix} v_x(t) \\ v_y(t) \\ \Omega_z(t) \end{bmatrix}, \tag{9}$$

where $\omega_i(t)$ is the rotational velocity of wheel i (i = 1…4), $v_x(t)$, $v_y(t)$ are the linear and angular velocities of the robot in Cartesian space, l_1 and l_2 are the distances between wheels contact points on longitudinal and transversal directions, R is the wheel radius.

Robot control

Because of the complex problems that should be solved to command and control a mobile robot, hierarchical *top-down* architecture is adopted. This allows us to make changes of a control structure module, with minimum influence to the global system functionality. Each control level communicates in a chosen way (in our case *CANopen* protocol) with the down level and also receives information about the robot state. This information is analyzed in order to take decisions for the next step of the robot control.

In a *top-down* strategy, the robot control architecture can be divided in two distinct problems (Fig. 7):

- Motor control;
- Motion control.

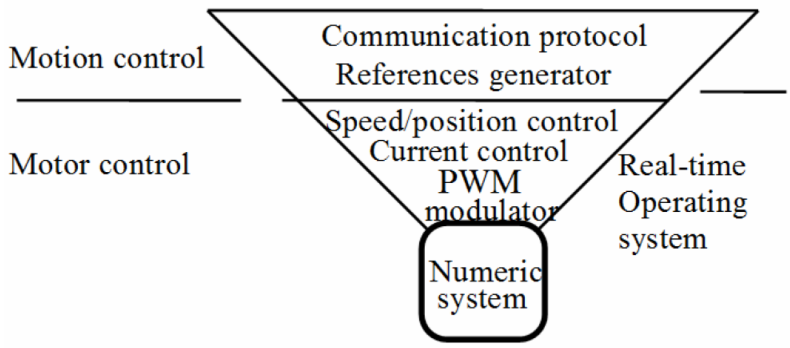

Fig. 7 Robot control strategy architecture

A Motorola phyCORE-mpc555 module is responsible for global motion control of the robot and four servo-amplifiers (Maxon 4-Q-EC DES 70/50 *Digital Electronic Commutation Servo-amplifier*) are used to control the four *brushless AC* motors (Maxon EC60-400). The hardware control architecture of our omni-directional mobile robot is shown in Fig. 8.

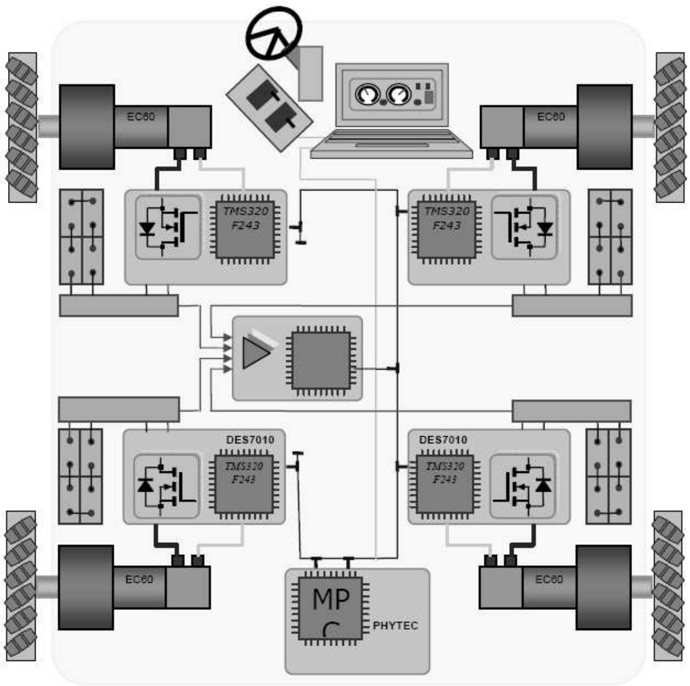

Fig. 8 Robot control hardware architecture

In a real-time application, researchers should solve some problems, as follow:

- To interface the numeric system with the controlled system;
- To interface the operating system and the higher hierarchical level;
- To develop programs starting from the existence of a real-time operating node.

In our case, the motor interfacing was realized using four DES 70/50 servo-amplifiers. They are controlled via a Controller Network Area, the central control unit (high level) being a phyCORE-mpc555 module. A general overview of the robot control architecture is shown in Fig. 9. This level could also include a trajectory planning module, when the robot should be autonomous, or may include an interface to the human operator, when the robot is controlled by a human. For the second option, a commercial FF380 Force Feedback Race Master has been used.

Summary

The development of an omni-directional vehicle was pursued to further prove the effectiveness and the maneuverability of this type of architecture. Such a vehicle with four Mecanum wheels provides omni-directional movement without needing a conventional steering system. Two wheel designs have been used for experimental tests in order to improve the wheel traction force. Till now, the robot is controlled by a human operator using a commercial FF380 Force Feedback Race Master interface.

In the next future, the control architecture will also include a trajectory planning module and the robot could be autonomous.

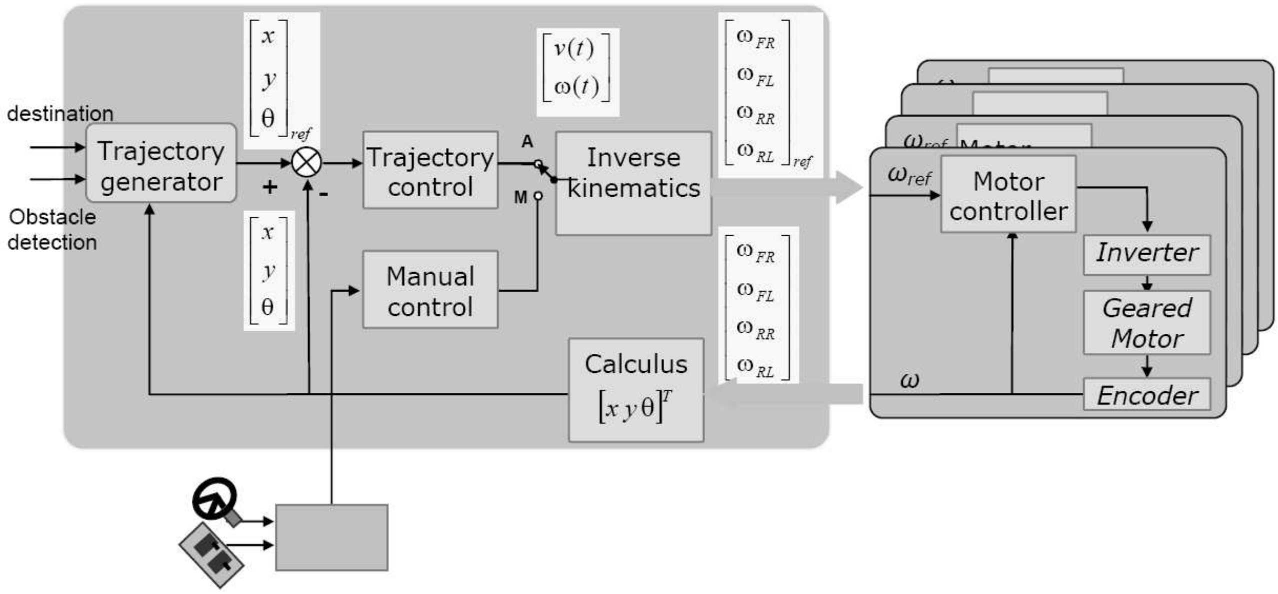

Fig. 9 General distributed control architecture

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