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Omnidirectional Mobile Robot – Design and Implementation

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1. Introduction

Industrial and technical applications of mobile robots are continuously gaining in importance. They are already widely used for surveillance, inspection and transportation tasks. A further emerging market is that of mobile entertainment robots.

One of the main requirements of an autonomous mobile robot is its ability to move through the operational space, avoiding obstacles and finding its way to the next location, in order to perform its task, capabilities known as localization and navigation. In order to know where to go, the robot must have accurate knowledge of its current location. It means, it should use a great variety of sensors, external references and algorithms.

In order to move in tight areas and to avoid obstacles mobile robots should have good mobility and maneuverability. These capabilities mainly depend on the wheels design. Research is continuously going on in this field, to improve the autonomous navigation capability of mobile robotic systems.

This chapter introduces an omnidirectional mobile robot for educational purposes. The robot has full omnidirectional motion capabilities, thanks to its special Mecanum wheels. The present chapter provides some information about conventional and special wheels designs, mechanical design aspects of the Mecanum wheel and also of the robot, kinematic models, as well as electronics and control strategies: remote control, line follow, autonomous strategy. Thanks to its motion capabilities and to its different control possibilities, the robot discussed in this chapter could be used as an interesting educational platform. This report is the result of a research conducted at the Robotics Laboratory of the Mechanical Engineering Faculty, "Gh. Asachi" Technical University of Iasi, Romania.

2. Previous work

There are two types of omnidirectional wheeled platforms: one type is using special wheels, and the other type includes conventional wheels. Special wheels, which have been mostly studied for the omnidirectional mobile platforms, have an active tracking direction and a passive moving direction. Conventional wheels can be broken into two types, caster wheels and steering wheels.

The Mecanum wheel was invented in 1973 by a Swedish engineer (Mecanum Company), named Ilon (Ilon, 1975). This is why it is called Mecanum or Swedish wheel. Using four of these wheels provides omni-directional movement for a vehicle without needing a

conventional steering system (Muir & Neumann, 1990; Dickerson & Lapin, 1991; Braunl, 1999).

The first mobile robot with Mecanum wheels (named "Uranus"), quite similar to our vehicle, was designed and constructed in Carnegie Mellon University (Muir & Neuman, 1987a and 1987b), see Fig. 1. It had not a suspension system, which is absolutely necessary if the ground is not completely flat.
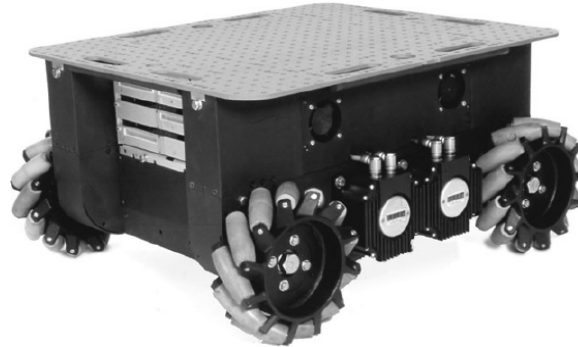

Figure 1. Uranus omnidirectional mobile robot [Muir & Neuman, 1987]

The benefits of a vehicle with Mecanum wheels relative to one with steered wheels have been presented by (Dickerson & Lapin, 1991). (Muir & Neuman, 1987a and 1987b) introduced the kinematic model and developed an algorithm for feedback control of Uranus, which consists of four Mecanum wheels, similarly to our platform, except the suspension.

Many other projects with four Mecanum wheels have been presented by (Diegel et al., 2002; Koestler & Braunl, 2004; Siegwart & Nourbakash, 2004; Efendi et al., 2006; etc.).

Omnidirectional wheeled vehicles with Mecanum wheels have some shortcomings. According to (Nagatani et al., 2000), a vehicle with Mecanum wheels is susceptible to slippage, and as a result, with the same amount of wheel rotation, lateral traveling distance is different from longitudinal traveling distance. In addition, the ratio of longitudinal traveling distance over lateral traveling distance with the same amount of wheel rotation, changes with ground condition. The second drawback is that the contact point between the wheel and the ground moves along a line parallel to the wheel axis, even though the wheel is always in contact with the ground. The lateral movement produces horizontal vibrations. The last drawback is that its ability to overcome obstacles is not independent of travel direction.

The slippage of the wheels prevents the most popular dead-reckoning method, using rotary shaft encoders (Everett, 1995 and Borenstein et al, 1996), from being performed well on a vehicle with Mecanum wheels. In order to solve the problem, visual dead-reckoning was used as a slip-resilient sensor (Giachetti et al, 1998 and Nagatani et al, 2000). This technique, also used in optical mice, makes use of an on-board video-camera continuously capturing frames of the ground beneath and image processing hardware on the robot determining the speed and direction in which the current frame has moved relative to the previous frame thus allowing the speed and direction of that point of reference to be calculated.

Basically, our approach is similar to above ideas. However, we do not rely on only visual information for positioning, but we use the information to support odometry system.

3. Omnidirectional mobility

The term of omnidirectional is used to describe the ability of a system to move instantaneously in any direction from any configuration.

Robotic vehicles are often designed for planar motion; they operate on a warehouse floor, road, lake, table etc. In such a two dimensional space, a body has three degrees of freedom. It is capable of translating in both directions and rotating about its center of gravity. Most conventional vehicles however do not have the capability to control every degree of freedom independently. Conventional wheels are not capable of moving in a direction parallel to their axis. This so called non-holonomic constraint of the wheel prevents vehicles using skid-steering, like a car, from moving perpendicular to its drive direction. While it can generally reach every location and orientation in a 2D space, it can require complicated maneuvers and complex path planning to do so (Fig. 2). This is the case for both human operated and robotic vehicles.
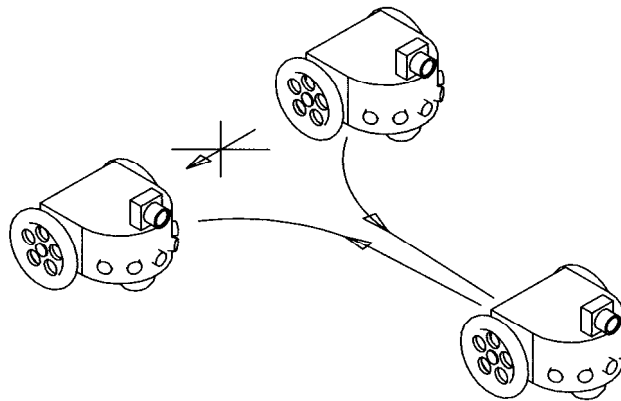
Figure 2. Lateral parking of a differential drive mobile robot

When a vehicle has no non-holonomic constraints, it can travel in every direction under any orientation. This capability is widely known as omnidirectional mobility.

Omnidirectional vehicles have great advantages over conventional (non-holonomic) platforms, with car-like Ackerman steering or differential drive system, for moving in tight areas (Borenstein et al., 1996). They can crab sideways, turn on the spot, and follow complex trajectories. These robots are capable of easily performing tasks in environments with static and dynamic obstacles and narrow aisles. Such environments are commonly found in factory workshop offices, warehouses, hospitals, etc. Flexible material handling and movement, with real-time control, has become an integral part of modern manufacturing. Automated Guided Vehicles (AGV's) are used extensively in flexible manufacturing systems to move parts and to orient them as required.

In contrast, non-holonomic robots can move in some directions (forward and backward) and describe some curved trajectories but can not crab sideways. For example, for parallel parking, a differential drive robot should make a series of maneuvers (see Fig. 2). A car-like robot can not even turn in place; Figure 3 illustrates this point. The shaded circles to the right and left of the vehicle are inaccessible areas for Ackerman steered platforms due to the mechanical system that dictates the minimum turning radius.
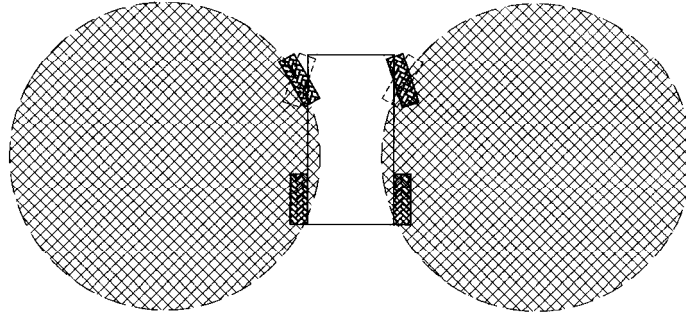
Figure 3. Mobility of a car-like mobile robot

The development of an omnidirectional vehicle was pursued to further prove the effectiveness of this type of architecture and to add a ground vehicle platform that is capable of exceptional maneuverability. Omnidirectional vehicles are divided into two categories that describe the type of wheel arrangement they use for mobility: conventional wheel designs and special wheel designs.

4. Wheel designs

4.1. Conventional wheel designs

Conventional wheels designs used for mobile robots with omnidirectional capabilities can be broken into two types, caster wheels and steering wheels. They have larger load capacities and a higher tolerance for ground irregularities compared to the special wheel configurations. However, due to their non-holonomic nature, they are not truly omni-directional wheels. These designs are not truly omni-directional because when a move with a non-continuous curve is encountered there is a finite amount of time before the steering motors can reorient the wheels to match the projected curve (Dubowski et al., 2000). The time constant of this process is assumed much faster than the gross vehicle dynamics for most applications. Therefore, it is assumed to be capable of zero-radius trajectories and retains the term omni-directional. Most platforms that contain conventional wheels and approximate omni-directional mobility incorporate at least two independently steered and independently driven wheels (Borenstein et al., 1996). Active Castor wheels like the one shown in Fig. 4 or conventional steered wheels (Fig. 5} can be used to achieve this near omni-directional mobility.
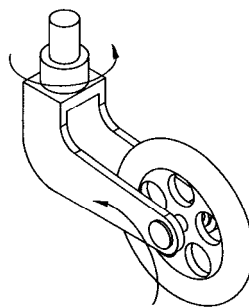

Figure 4. Active Castor wheel
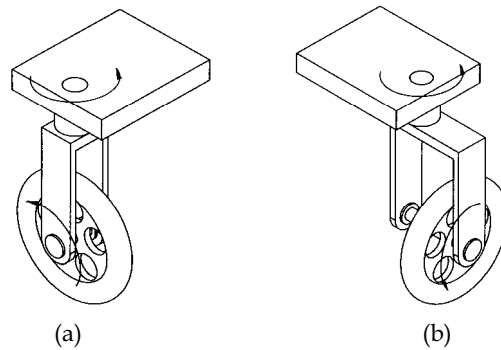
(a)   (b)

Figure 5. Steered wheel: (a) powered steering wheel; (b) lateral offset

4.2. Special wheel designs

Special wheel designs are based on a concept that actives traction in one direction and allow passive motion in another, thus allowing greater flexibility in congested environments (Yu et al., 2000). These designs can include the universal wheel, the Mecanum (Swedish) wheel, and the ball wheel mechanism. The universal wheel (Fig. 6) provides a combination of constrained and unconstrained motion during turning. The mechanism consists of small rollers located around the outer diameter of a wheel to allow for normal wheel rotation, yet be free to roll in the direction parallel to the wheels axis. The wheel is capable of this action because the rollers are mounted perpendicular to the axis of rotation of the wheel. When two or more of these wheels are mounted on a vehicle platform their combined constrained and unconstrained motion allows for omni-directional mobility.

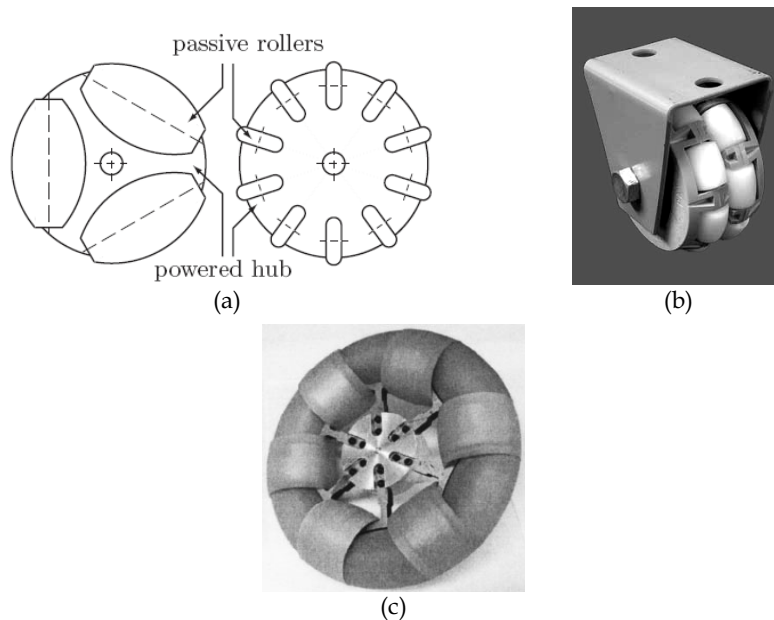(a)   (b)

(c)

Figure 6. Universal wheel: (a) simple; (b) double; (c) alternate

The Mecanum (Swedish) wheel is similar to the universal wheel in design except that its rollers are mounted on angles as shown in Fig. 7. This configuration transmits a portion of the force in the rotational direction of the wheel to a force normal to the direction of the wheel. The platform configuration consists of four wheels located similarly to that of an automobile. The forces due to the direction and speed of each of the four wheels can be summed into a total force vector, which allows for vehicle translation in any direction.

Another special wheel design is the ball wheel mechanism. It uses an active ring driven by a motor and gearbox to transmit power through rollers and via friction to a ball that is capable of rotation in any direction instantaneously. An illustration of this type of wheel is shown in Fig. 8.

Each of these mentioned designs with special wheels achieve excellent maneuverability, but are limited to hard even surfaces due to the small roller diameters.

An overview of the properties of some of these designs is given in Table 1.

| Universal wheel (simple)	+ low weight, compact design + simple mechanical design + commercially available	- discontinuous wheel contact or variable drive-radius - sensitive to floor irregularities
Mecanum wheel	+ compact design + high load capacity	- discontinuous wheel contact - high sensitivity to floor irregularities - complex wheel design
Powered steered wheel	+ continuous wheel contact + high load capacity + robust to floor conditions	- heavy and bulky design - high friction and scrubbing while steering - complex mechanical design
Castor wheel	+ continuous wheel contact + high load capacity + low scrubbing force during steering + robust to floor conditions	- voluminous design - transmit power and signal across rotational joints - complex mechanics

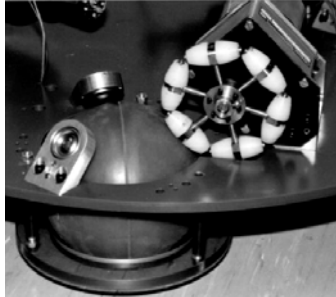Table 1. Properties of wheel designs
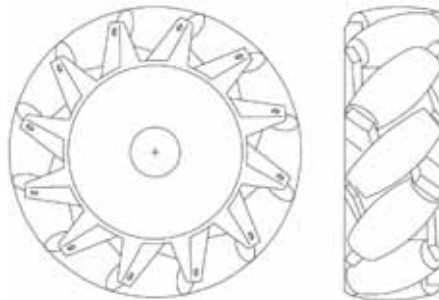
Figure 7. Mecanum wheel

Figure 8. Ball wheel [Yu et al., 2000]

5. Mecanum wheel design

One of the more common omnidirectional wheel designs is that of the Mechanum wheel, invented in 1973 by Bengt Ilon, an engineer with the Swedish company Mecanum AB (Ilon, 1975). The wheel itself consists of a hub *1* carrying a number of free moving rollers *2* angled at 45° about the hub's circumference (Fig. 9).

Because the solution shown in Fig. 6 is more difficult to manufacture, a simpler wheel hub has been chosen (Fig. 10).

The angle between rollers axis and central wheel axis could have any value but in the case of conventional Swedish wheel it is 45˚. 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 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 changing of the wheels themselves.
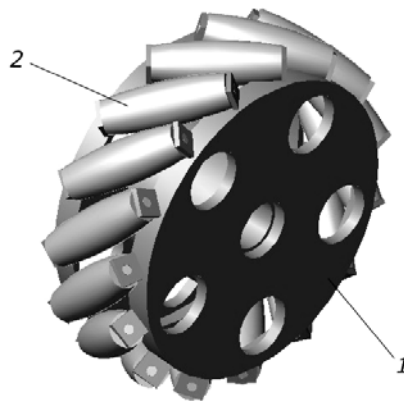

Figure 9. Basis components of Mecanum wheel

The rollers are shaped such that the silhouette of the omni-directional wheel is circular (Fig. 10.a). We can get the shape of a roller if we cat a 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 $\gamma = 45˚$ (Fig. 11).

This shape should respect the equation:

$$\frac{1}{2}x^2 + y^2 - R^2 = 0 .$$ (1)

where R is the external radius of the wheel.

If the roller length, L_r, is much smaller than the wheel external radius, R, then the roller shape could be approximated with a circle arc having $2R$ as radius.
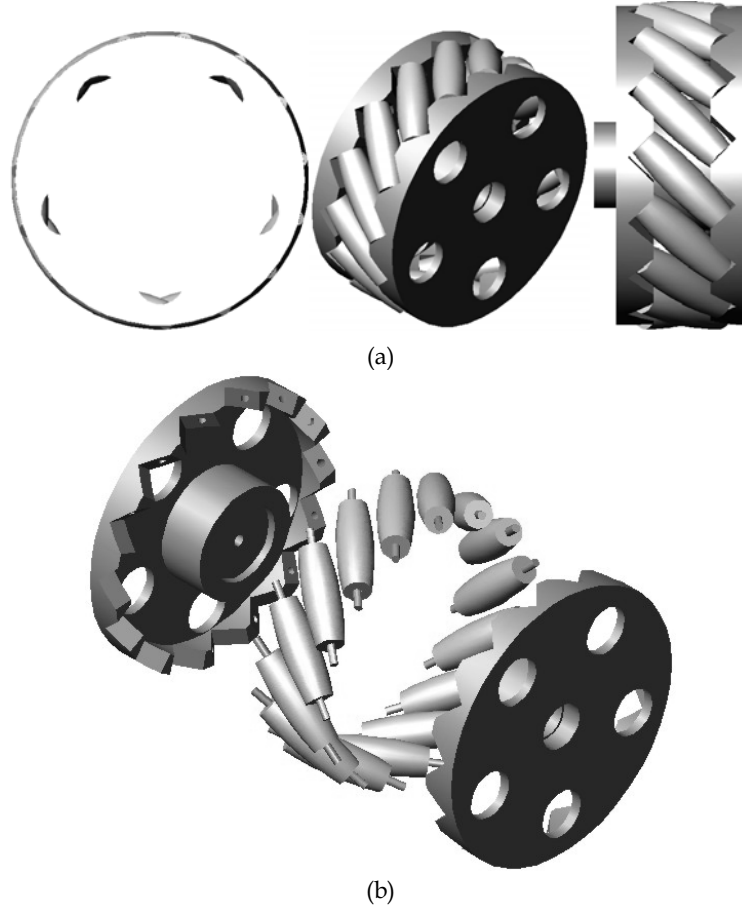

(a)

(b)

Figure 10. Mecanum wheel: (a) front (silhouette), 3D and left views; (b) exploded view

In order to get a circular silhouette for the wheel (see Fig. 10.a), a minimum number of rollers should be computed (Fig. 12). According to Fig. 12, if the roller length is chosen, L_r, we get the number of rollers, n,

$$n = \frac{2\pi}{\varphi} ,$$ (2)

where:

$$\varphi = 2\arcsin\left(\frac{L_r}{2R\sin\gamma}\right).$$

(3)

If we assume that the number of rollers n is known, we can get the roller length:

$$L_r = 2R\frac{\sin\dfrac{\varphi}{2}}{\sin\gamma} = 2R\frac{\sin\dfrac{\pi}{n}}{\sin\gamma}.$$

(4)

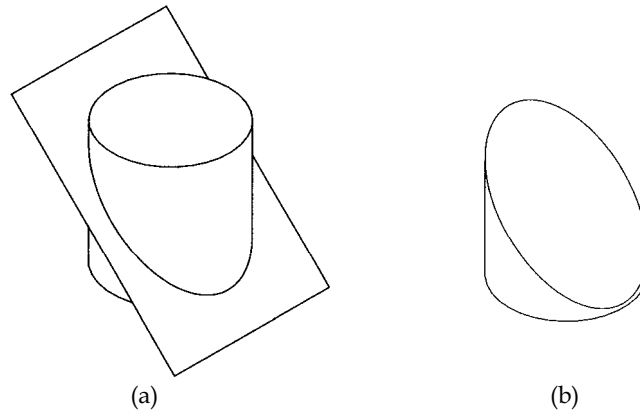(a)   (b)

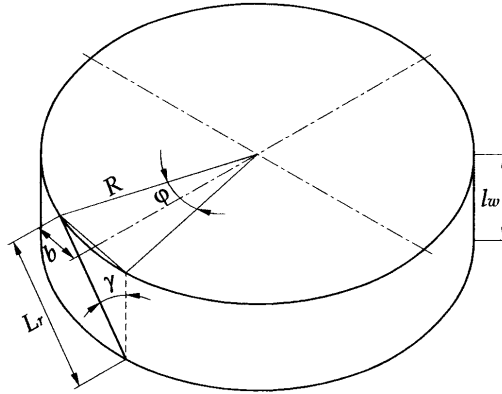Figure 11. Roller shape: (a) cylinder sectioned by a plane; (b) resulted shape

Figure 12. Wheel parameters

The wheel width will be:

$$l_w = L_r\cos\gamma = 2R\frac{\sin\dfrac{\pi}{n}}{\tan\gamma}.$$

(5)

In our case, $\gamma = 45°$, it means:

$$L_r = 2\sqrt{2}R\sin\frac{\pi}{n},\tag{6}$$
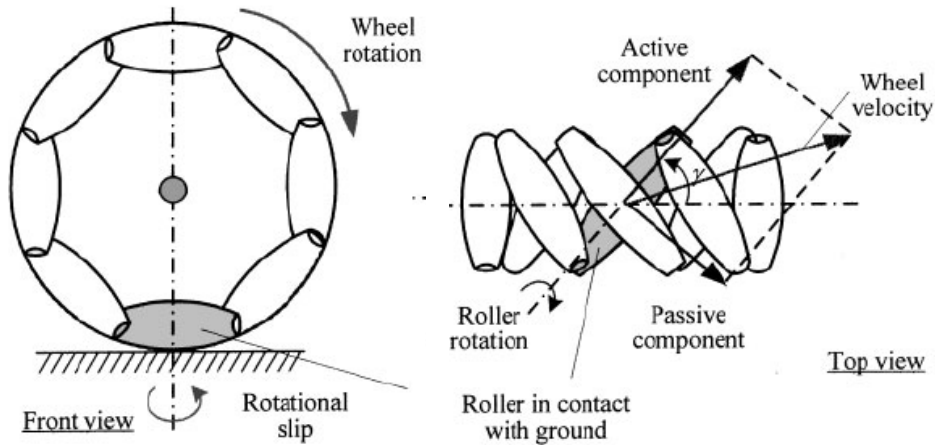
$$l_w = 2R\sin\frac{\pi}{n}.\tag{7}$$

Figure 13. DOFs in a Mecanum wheel [Song & Byun, 2004]

The rollers are neither actuated nor sensed. The key advantage of this design is that, although the only wheel rotation is powered along the main axis, the wheel can kinematically move with very little friction along many possible trajectories, not just forward and backward (Siegwart & Nourbakash, 2004).

A Swedish omnidirectional wheel has 3 DOFs composed of wheel rotation, roller rotation, and rotational slip about the vertical axis passing through the point of contact (see Fig. 13). In the omnidirectional wheel, the wheel 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.

6. Robot design

6.1 Mechanical design

Typical Mecanum-wheel based vehicles have a square or rectangular configuration, with two wheels on each side of the chassis. Using four of these wheels provides omni-directional movement for a vehicle without needing a conventional steering system. In our case, we have chosen a square configuration, in order to simplify the mathematical model and, obviously, the motion control of it (Fig. 14). Our robot is a 450 [mm] long, 382 [mm] wide and 220 [mm] high platform.

Each wheel is actuated by its own DC geared MAXON motor. Because the omni-directional capability of the robot depends on each wheel resting firmly on the ground, some are equipped with suspension systems. Even if these designs are for indoor applications (this

means they are moving on flat surfaces), having four wheels, they need a suspension system just in case of small waves that could exist on the ground. In our case, a passive suspension system with two spatial four-bar mechanisms ($ABCD$ and $A'B'C'D'$, serial connected) is used, in order to easy adapt the system to the ground (Fig. 15).
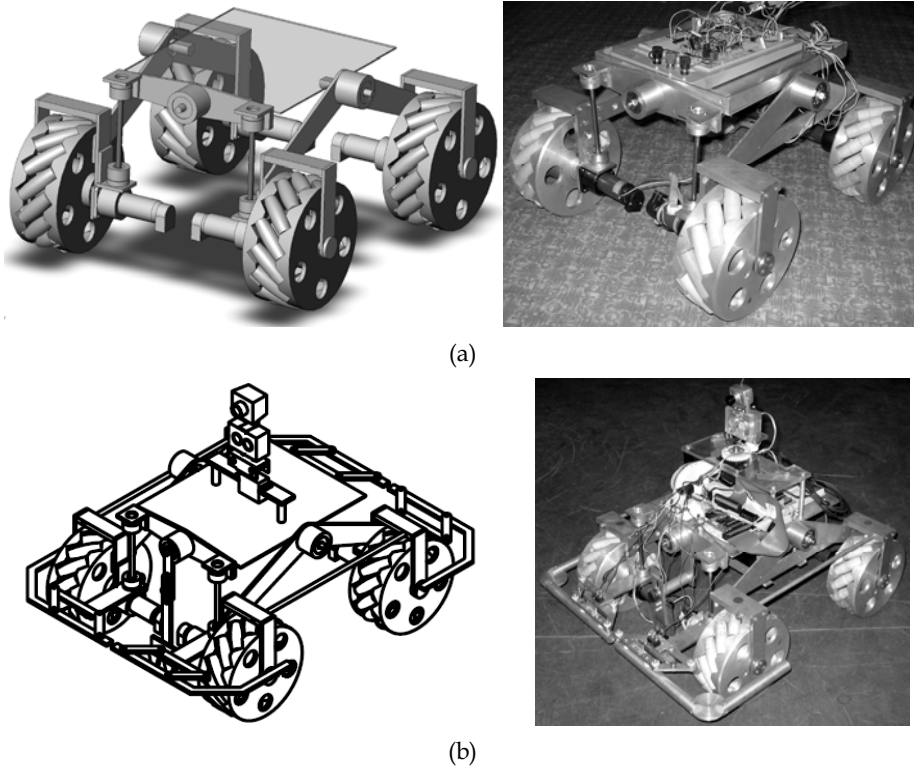

(a)

(b)

Figure 14. Omnidirectional robot: (a) CAD design and photo of the first prototype; (b) the second prototipe

(a)   (b)
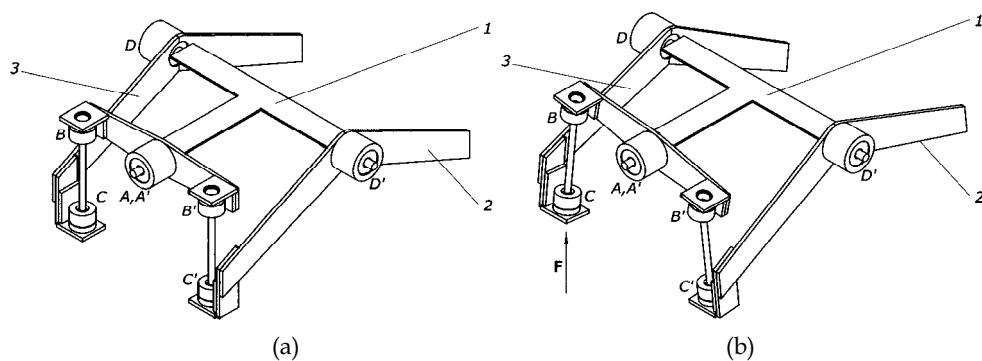
Figure 15. Suspension mechanism: (a) its position in case of even terrain; (b) uneven terrain
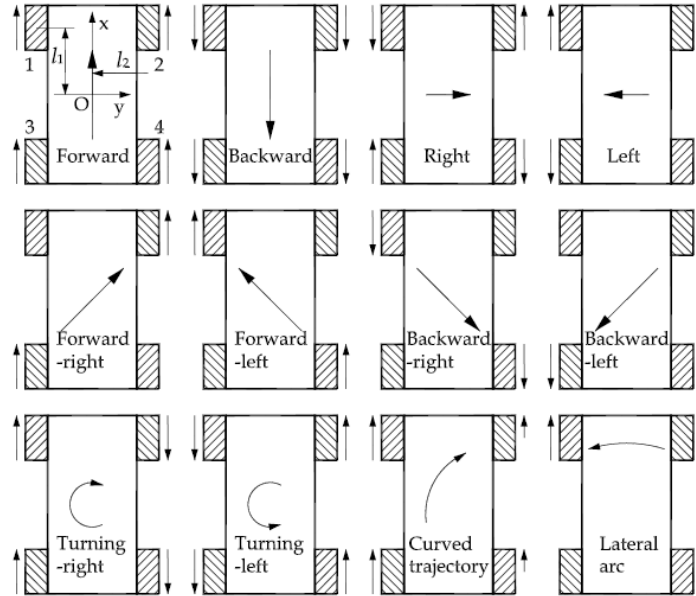
Figure 16. Robot motion according to the direction and angular speed of the wheels

The robot is able to translate on any direction, forward/backward but also sideways left/right, and turning on the spot, thanks to its special wheels (Fig. 16). This is especially helpful when having to maneuver in a tight environment such as a factory floor. The control procedure described in Fig. 16 is only valid for the actual solution of rollers orientation. The robot has been designed is such way that the front and rear wheels of right or left side could be exchanged between them. In such conditions (of changing the front and rear wheels) the control procedure will be totally different.

At this time, three solutions for motion control are implemented in the microcontroller:

- Remote control mode;
- Line-follower mode;
- Autonomous mode, thanks to an ultrasonic pair sensors and bumper bars.

Because a single pair of ultrasonic sensors is used, the module is always swinging using a servo and a supplementary gear transmission, mounted on the top of the robot. Even if the servo has an angular stroke of 180°, thanks to the gear transmission, the sensor is able to scan an angle of 360°. To avoid obstacle collisions when the robot is going backward for an obstacle avoiding, and also when it run into an obstacle under a small angle, two supplementary pairs of switches have been added (one pair in the front and one in the back).

6.2 Kinematics

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 (Fig. 16).

If we consider a $x_S O_S y_S$ frame attached to the robot chassis (see Fig. 17), we can write the body speed equations as follow:

$$\begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = \frac{R}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & -1 & 1 \\ -\dfrac{1}{l_1+l_2} & \dfrac{1}{l_1+l_2} & -\dfrac{1}{l_1+l_2} & \dfrac{1}{l_1+l_2} \end{bmatrix} \cdot \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} \tag{8}$$

where: R is the wheel radius; ω_i is the angular velocity of the wheel i ($i = 1..4$); l_1, l_2 are the distances between wheel axis and body center.

If the speed of the robot is imposed, we have to compute the angular speed of each wheel (inverse velocity solution):

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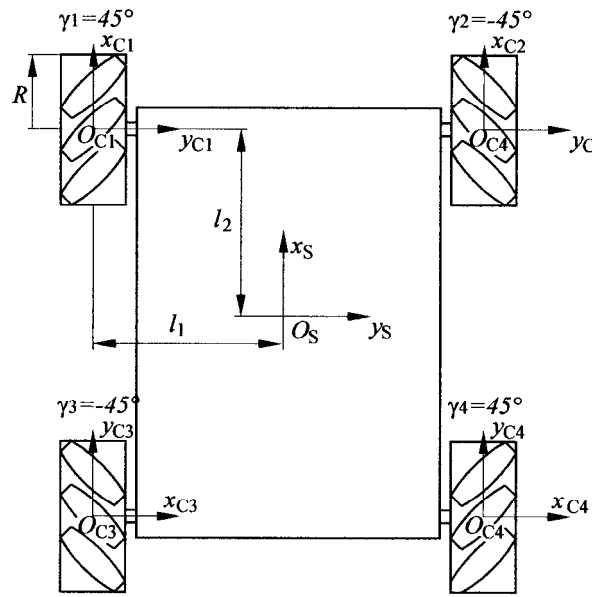

Figure 17. Kinematics of the robot

6.3 Electronics

As we have mentioned before, the robot can be remote controlled, using a command system (Fig. 18), or it can follow a line or to be autonomous, using an ultrasonic sensor for obstacle avoidance.

In order to receive commands from the system presented in Fig. 18, or to detect obstacles and to drive the motors, an electronics board based on a PIC16F876 microcontroller, and placed on the robot, is used (Fig. 19).
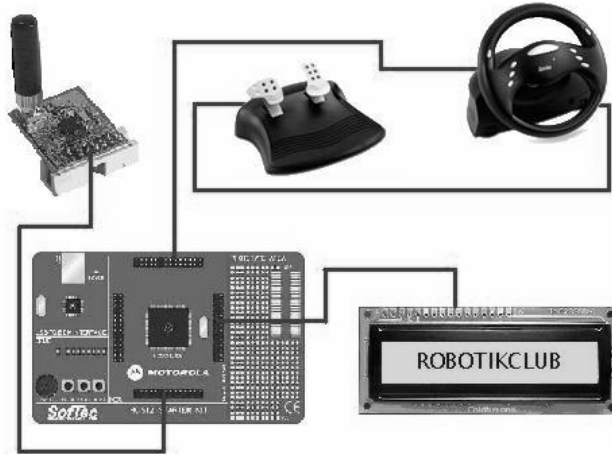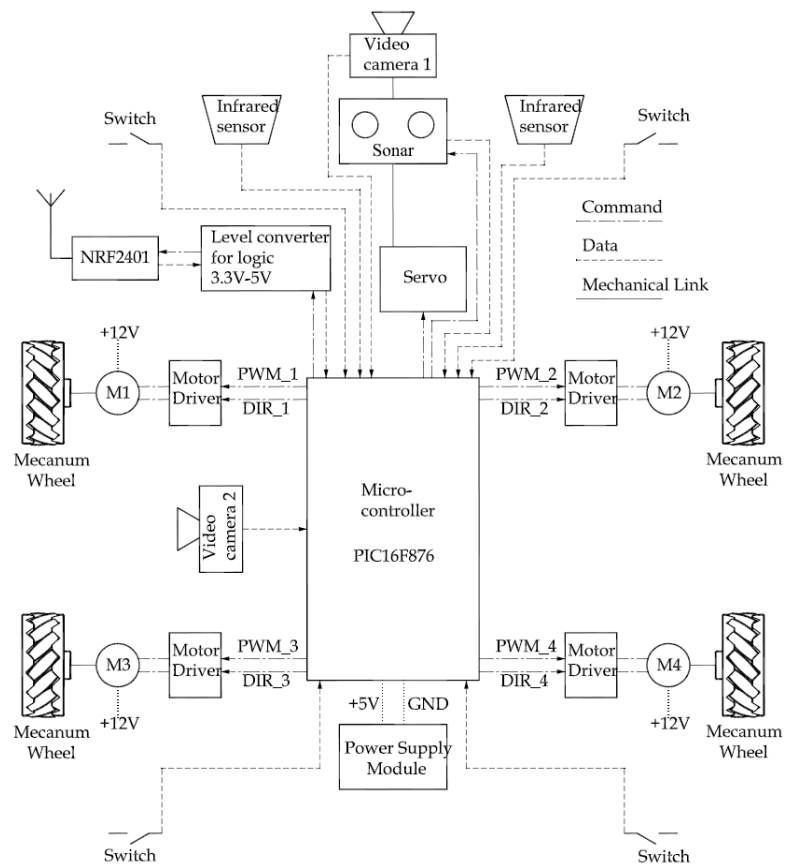
Figure 18. Command system

Figure 19. Electronic board

7. Robot control

The aim of this project was to provide the platform with motion control that could be programmed to accommodate various robotic behaviours specified.

7.1 Line follower mode

Fixed line following is the simplest and most reliable solution, yet is also the most limiting. A physical line is marked on the ground along the path which the robot is to follow (Everett, 1995 and Borenstein et al, 1996). For a robot that is set up in a fixed location for a set task this system is effective but for a research robot with omni-directional capability this approach is seen to be a primitive, though still viable, option.

The main application of this platform being education, line following remain interesting for the students. We have used two OPB704 infrared sensors.

7.2 Remote control mode

The robot can be remote controlled, using a command system (Fig. 18), and the electronic board (Fig. 19). A steering wheel set is used as a main driving element and two transmitters/receivers based on the NRF2401 circuit, in order to transmit commands to the robot and to receive data from it.

Because the robot can be controlled outside the room where we have the fixed command system, a video camera (video camera 1 in Fig. 19) will transmit all the time images from the robot working space. In such way, we are able to see everything around the vehicle and we can act according to the data received from the video camera.

7.3 Autonomous mode

To avoid obstacles in autonomous mode, a pair of ultrasonic sensor and two contact switches (two in the front and two in the back) have been used. Because a single pair of ultrasonic sensors is used, the module sonar-camera is always swinging using a servo and a supplementary gear transmission, mounted on the top of the robot. Even if the servo has an angular stroke of 180˚, thanks to the gear transmission, the sensor is able to scan an angle of 360˚. To avoid obstacle collisions when the robot is going backward for an obstacle avoiding, and also when it run into an obstacle under a small angle, two supplementary pairs of switches have been added (one pair in the front and one in the back).

To simplify the control and to reduce the time for the distance measuring procedure, the servo (and ultrasonic sensor) is swinging between two limits ($-\alpha_{max}$, $-\alpha_{min}$). The robot velocity along x_S axis depends on $\sum_i D_i p_v$ and its angular velocity depends on $\sum_i D_i p_\omega$, where: D_i is the distance measured to the obstacle, for α_i angular position of the servo (Fig. 20); p_v and p_ω are the computing coefficients for linear and angular speed, respectively.

If the distance to the obstacle becomes smaller than a minimum imposed value, the linear speed will be zero (the robot stop) and the vehicle will turn, finding an "exit". If this turning motion takes a long time (this time becomes bigger than a maximum imposed value), the servo will swing for the maximum limits (from -180˚ to +180˚) finding a faster solution. This could happen when the robot is entering in a closed space.

If during the movement of the robot it will get an impact with an obstacle (one of the front switches is ON), the vehicle will go backward and will continue turning, and then it will try again to go forward.

The wheel slip is a common problem with the Mecanum wheel, particularly when the robot moves sidewise, as it has only one roller with a single point of ground contact at any one time. This severe slippage prevents the most popular dead-reckoning method, using rotary shaft encoders (Everett, 1995 and Borenstein et al, 1996), from being performed well on the Mecanum robot. To cope with the problem, visual dead-reckoning was used as a slip-resilient sensor (Giachetti et al, 1998; Nagatani et al, 2000 and Kraut, 2002). This technique, also used in optical mice, makes use of an on-board video-camera continuously capturing frames of the ground beneath (example in Fig. 21) and image processing hardware on the robot determining the speed and direction in which the current frame has moved relative to the previous frame thus allowing the speed and direction of that point of reference to be calculated.

The second video camera is used for ground image capture, fixed under the chassis of the robot.
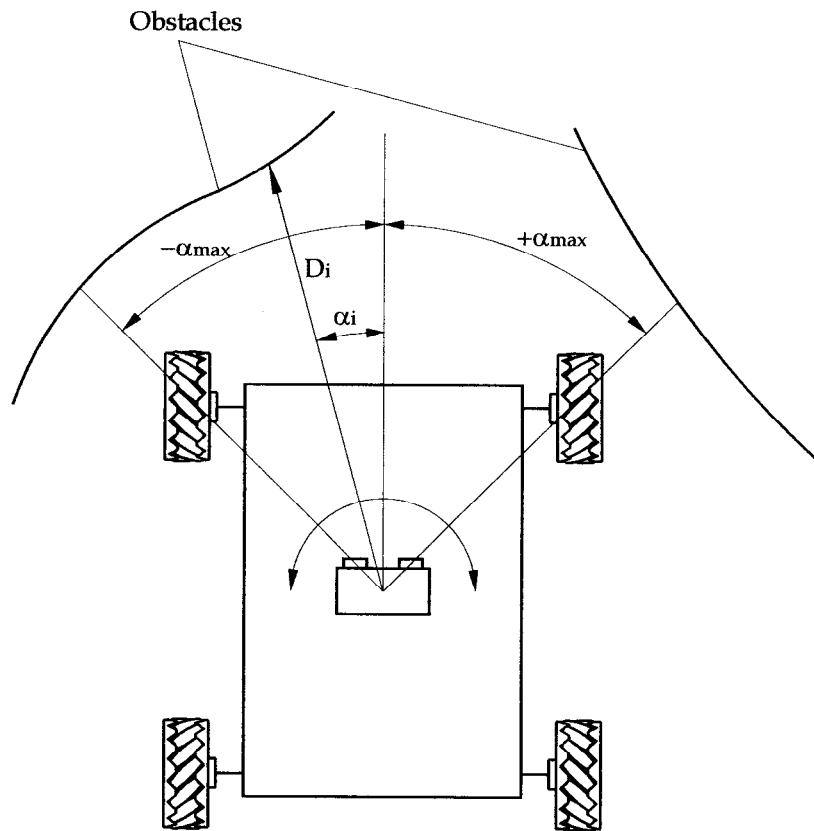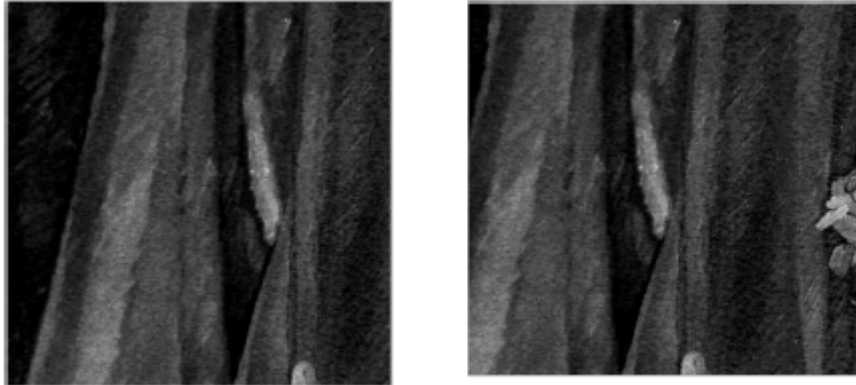

Figure 20. Obstacle avoidance

Figure 21. Image capture: (a) previous image; (b) current image

8. Conclusion

Omnidirectional vehicles have great advantages over conventional (non-holonomic) platforms, with car-like Ackerman steering or differential drive system, for moving in tight areas. They can crab sideways, turn on the spot, and follow complex trajectories. These robots are capable of easily performing tasks in environments with static and dynamic obstacles and narrow aisles. Such environments are commonly found in factory workshop offices, warehouses, hospitals, etc. Flexible material handling and movement, with real-time control, has become an integral part of modern manufacturing.

The development of an omnidirectional vehicle was pursued to further prove the effectiveness of this type of architecture and to add a ground vehicle platform that is capable of exceptional maneuverability. Omni-directional vehicles are divided into two categories that describe the type of wheel arrangement they use for mobility: conventional wheel designs and special wheel designs.

This chapter introduced an omnidirectional mobile robot with Mecanum wheels for educational purposes. The robot has full omnidirectional motion capabilities, thanks to its special Mecanum wheels. Some information about conventional and special wheels designs, mechanical design aspects of the Mecanum wheel and also of the robot, kinematic models, as well as electronics and control strategies have been presented. Thanks to its motion capabilities and to its different control possibilities, the robot discussed in this chapter could be used as an interesting educational platform.

At this time, three solutions for motion control have been implemented in the microcontroller:

- Remote control mode;
- Line-follower mode;
- Autonomous mode, thanks to an ultrasonic pair sensors and bumper bars.

To know the position of the robot according to a reference point, a video camera was used for ground image capture.

9. References

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