Design and Development of an Autonomous Omni-Directional Mobile Robot with Mecanum Wheels

Mihai Olimpiu Tătar*, Cătălin Popovici, Dan Mândru*, Ioan Ardelean*, Alin Pleşa*

*Department of Mechatronics and Machine Dynamics
Technical University of Cluj-Napoca
Cluj-Napoca, România
Olimpiu.Tatar@mdm.utcluj.ro, Dan.Mandru@mdm.utcluj.ro, catalin.popovici@yahoo.com, ardelean@mdm.utcluj.ro, plesa.alin@gmail.com

Abstract— **In this paper the authors are presenting an omni-directional mobile robot, developed for educational and research purposes. The omni-directional motion capabilities of the robot are due to its special Mecanum wheels. The paper provides general information about Mecanum omni-directional wheels, mechanical design aspects of the wheels and the robot and it also describes the kinematic and dynamic models of the robot and the control system.**

Keywords— Mecanum wheel, Omni-directional, Robot

I. INTRODUCTION

Out of the great diversity of mobile robots which exist, the omni-directional mobile robots have the ability to move instantly in any direction from any configuration. An important role in their construction is held by their special (omni-directional) wheels.

Out of the large number of omni-directional wheels, the Mecanum wheels proved to be the best choice in driving vehicles in order to achieve maximum omni-directional efficiency.

This type of wheel is used in robotics applications which require a high level of manoeuvrability. An omni-directional Mecanum wheel has 3 DOF (Fig. 1). These are: wheel rotation (the first DOF), roller rotation (the second DOF), and rotational slip about the vertical axis passing through the point of contact (the third DOF.) [1], [2].

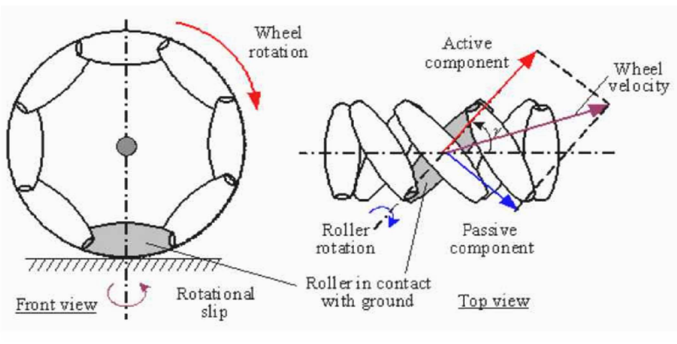


Figure 1. The degrees of freedom of a Mecanum wheel

978-1-4799-3732-5/14/$31.00 ©2014 IEEE

The omni-directional wheels are connected to the robot body, in most cases, and they do not rotate for steering, since steering can be performed by a combination of wheel rotation speeds.

According to [2], the wheel velocity can be divided into two components. The active component of the velocity is directed along the axis of the roller in contact with the locomotion surface, while the passive one is perpendicular to the roller axis.

The Mecanum wheels have the following advantages: compact design, high load capacity, simple to control, low speed and low pushing force when moving diagonally. As disadvantages, we can mention: discontinuous contact, high sensitivity to locomotion surface irregularities, complex design [3].

The omni-directional mobile robots have been investigated by many researchers in the last period [4], [5], [6], [7], [8].

Within this category of mobile robots, the mobile robots which use Mecanum wheels can perform important tasks in crowded environments with static and dynamic obstacles, in narrow aisles, such as those in offices, workshops, factories, warehouses or used to facilitate the care for the elderly or for hospital patients, etc [6], [9] .

Usually, the robots have four Mecanum wheels. The omni-directional capabilities of the robots depend on the contact between the wheel and the locomotion surface. In this respect, some Mecanum wheeled mobile robots are equipped with suspension systems.

Constructively, the typical Mecanum wheeled omni-directional mobile robots are square or rectangular shaped. The wheels are attached on both sides having the rollers oriented at angles of +45° and -45° [8], [10].

Because the wheel has a single point of contact with the locomotion surface at any given time, sliding is a common problem encountered by robots equipped with this type of wheels.

As an immediate result, for the same wheel rotation, the longitudinal travel distance is different from the transversal travel distance. Also, the ratio between the longitudinal and transversal travel distance is modified by the locomotion surface.

The paper is organized as follows: Section II shows the mechanical design aspects of the omni-directional wheels. Omni-directional robot development is presented in Section III and the robot control system in Section IV. The main directions of movement of the robot are presented in Section V. In Sections VI and VII are presented kinematic and dynamic modeling of the proposed omni-directional robot. Testing and discussion are presented in Section VIII, and finally in Section VIII some Conclusions of the paper are given.

II. THE DEVELOPED MECANUM WHEEL

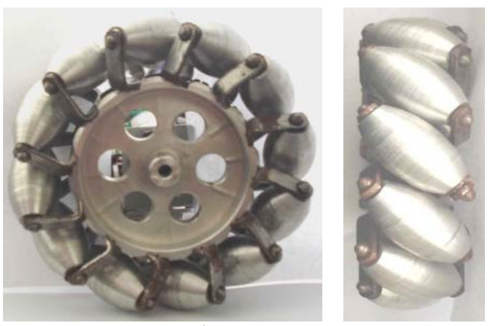
In order to improve manoeuvrability and practical applications of the robots in the last years, a variety of Mecanum wheel designs have been developed [11], [12].

The design of proposed wheel consists of a circular hub surrounded by the 12 rollers. The Hub and rollers are the main components of Mecanum wheel. On the circumference of the hub there is a special groove in which U-shaped elements are fixed with screws. In the U-shaped elements, the rollers are fixed at 45 degrees regarding the axis of the hub (Fig. 2 a, b).

The hub, the U-shaped elements and the rollers are all made of steel. Each roller has a diameter of 16 [mm] around the centre and 8 [mm] around the ends. The profile radius of the rollers is of 160 [mm]. The developed wheel has a radius R_w = 98 [mm] and a width of 28 [mm], (Fig. 2c). The wheel hub is actuated, while the rollers are idle.

Figure 2 shows the developed omni-directional wheel.

a) b)



c)

Figure 2. The Mecanum wheel. a), b) The 3D model c) The picture

III. THE DEVELOPED OMNIDIRECTIONAL ROBOT

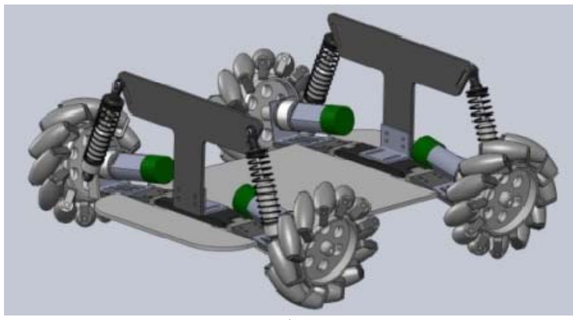
The developed omni-directional robot presented in this paper (Fig. 3a) has a simple shaped platform, with two T-shaped elements attached at the ends [13], [14].

The robot is driven by four geared DC motors. The motor shaft is connected directly to the hub of the Mecanum wheel. Each wheel is fitted with a suspension system mounted between the T-shaped elements and the mobile elements which hold the motor-wheel subassembly (Fig. 4).

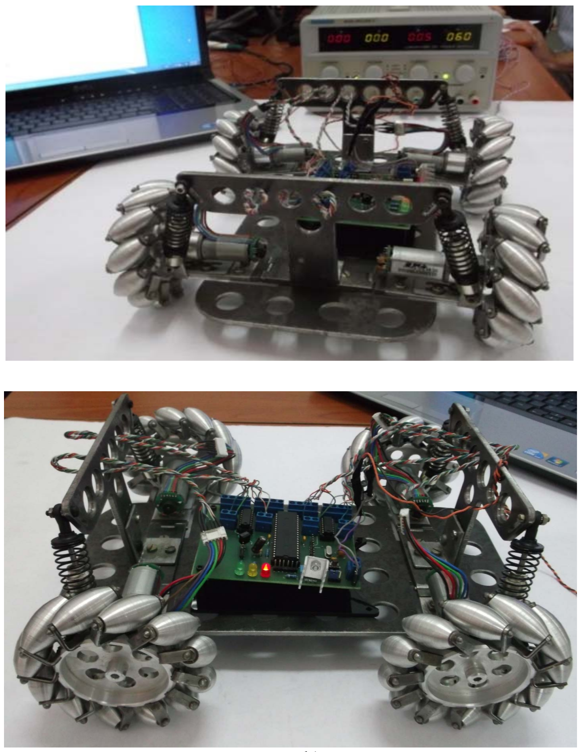
This design allows for the rollers to be in permanent contact with the locomotion surface, thus allowing a better performance on uneven surfaces.

The developed robot is not energetically autonomous, being constantly tethered to a power source.

The 3D model of the robot is shown in figure 3a and the pictures of the developed prototype are presented in figure 3b.



a)



b)

Figure 3. The Mecanum omni-directional robot a) The 3D model b) The picture

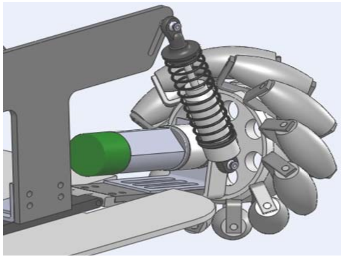


Figure 4. The suspension system of the robot

IV. THE CONTROL SYSTEM OF THE ROBOT

The electronic circuit presented in Figure 5 was developed for the control of the omni-directional robot. The components of the circuit are: ATMega 644 microcontroller, MHz extern oscillator, two L293D H-bridge drivers, TSOP34836 infrared sensor, LM7805 voltage stabilizer (Fig. 6). The omni-directional mobile robot can be controlled in two ways: by an infrared remote control or by a wireless PS2 joystick**.**

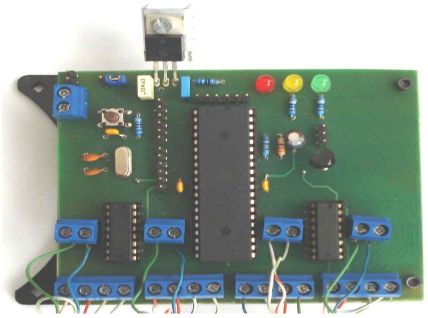


Figure 5. The picture of the electronic circuit

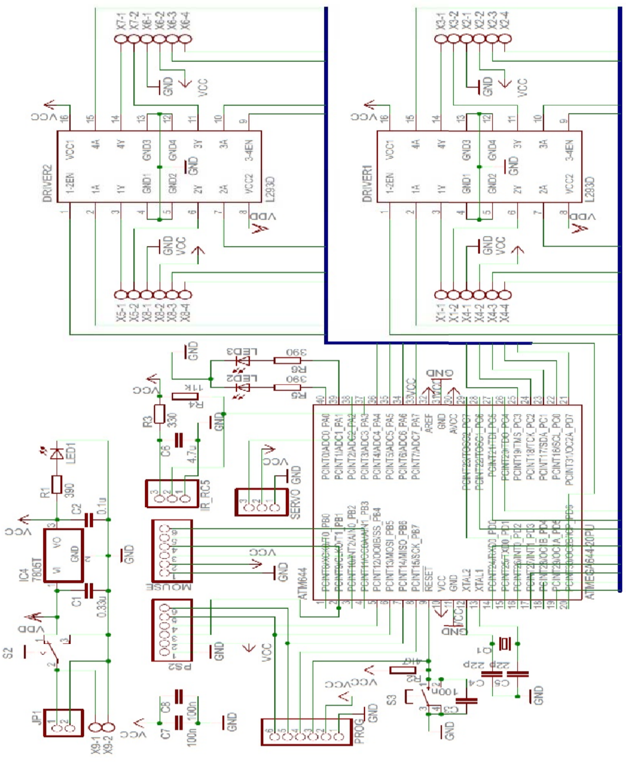


Figure 6. The electronic diagram of the control circuit

The structural scheme of the robotic system is presented in figure 7 [13].

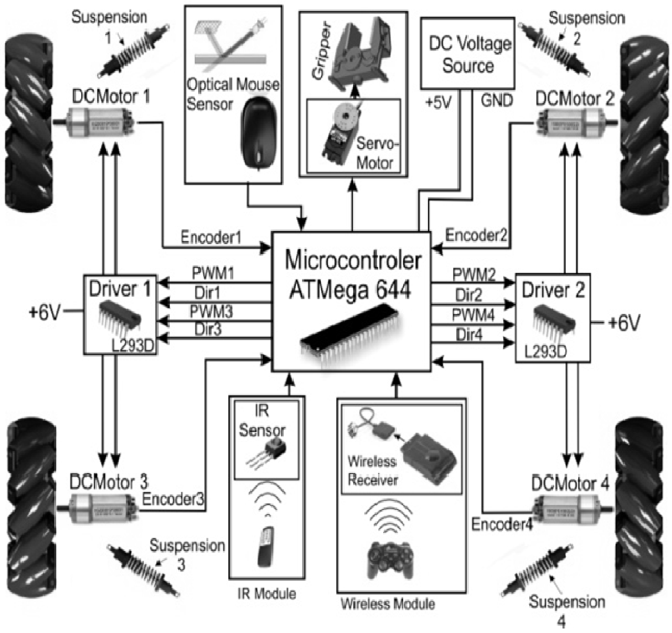


Figure 7. The main modules of the omni-directional robot

V. THE MAIN DIRECTIONS OF MOVEMENT OF THE ROBOT

The robot's main directions of movement, together with an indication of the rotation of each wheel, are shown in Figure 8. Following the mentioned directions, are possible by changing the rotation direction of the omni-directional wheels.

For example, the forward motion is achieved when all four wheels are driven in the same direction – forward (Fig 8 a). For the displacement in sideways (Fig. 8 c, d), diagonal pairs of wheels are driven in opposite directions.

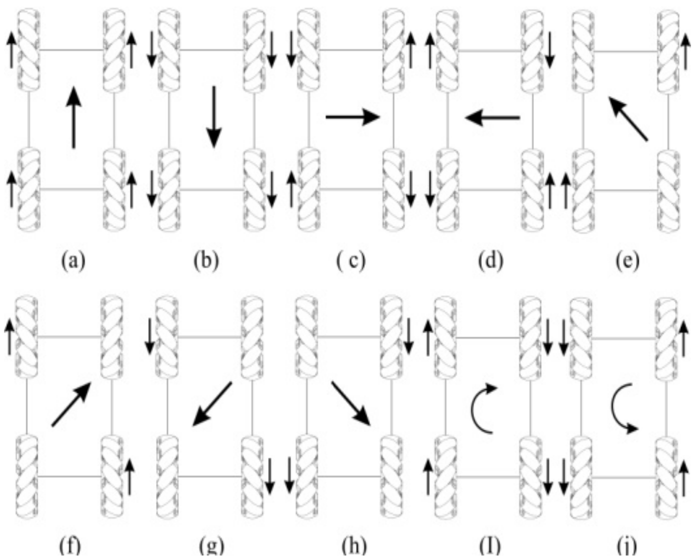


Figure 8. The main locomotion directions of the mobile robot and the way they are achieved

VI. THE KINEMATIC MODELING

Figure 9 shows the omni-directional robot wheel arrangement, the coordinate system attached to the frame, noted Σ_0 and the coordinate systems attached to the wheels, noted Σ_{iw} (i = 1,2,3,4) [15].

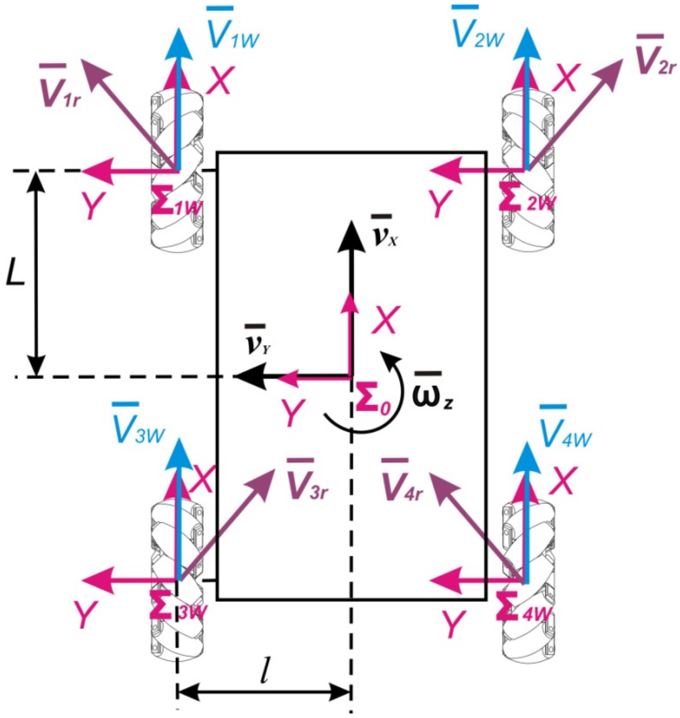


Figure 9. The geometry and disposition of the Mecanum wheels and frames

The following annotations were used for the wheels:

V_{iw} (i = 1, 2, 3, 4) - the velocity vector corresponding to wheel rotation,

V_{ir} (i = 1, 2, 3, 4) - the tangential velocity vector of the free roller touching the locomotion surface,

where $V_{iw} = \omega_{iw} R_w$, and R_W - is the radius of omni-directional wheel, ω_{iw} - is the angular velocity of the omni-directional wheel i.

The following annotations were used for the robot:

v_x , v_y – the linear speed components of the omni-directional robot on X and Y axes;

ω_z - the angular velocity of the omni-directional robot.

and:

L - the distance from each wheel shaft to the gravity centre of the robot on the X axis,

l - the distance from each wheel shaft to the gravity centre of the robot on the Y axis.

The inverse kinematic problem can be written as:

$$\mathrm{V_w} = \mathrm{J_0} \cdot \mathrm{V_0} \tag{1}$$

where $\mathrm{V_w} = [V_{1w} \quad V_{2w} \quad V_{3w} \quad V_{4w}]^T \in R^{4x1}$ is the wheel velocity vector corresponding to the angular velocity and $\mathrm{V_0} = [v_x \quad v_y \quad \omega_z]^T \in R^{3x1}$ the velocity vector in Cartesian coordinates.

The transformation matrix $\mathrm{J_0}$ can be expressed [15], [16]:

$$\mathrm{J_0} = \begin{bmatrix} 1 & -1 & -(l+L) \\ 1 & 1 & +(l+L) \\ 1 & 1 & -(l+L) \\ 1 & -1 & +(l+L) \end{bmatrix} \in R^{4x3} \tag{2}$$

The angular velocity of the wheels are given by the relation (1):

$$\begin{pmatrix} \omega_{1w}(t) \\ \omega_{2w}(t) \\ \omega_{3w}(t) \\ \omega_{4w}(t) \end{pmatrix} = \frac{1}{R_W} \cdot \begin{bmatrix} 1 & -1 & -(L+l) \\ 1 & 1 & (L+l) \\ 1 & 1 & -(L+l) \\ 1 & -1 & (L+l) \end{bmatrix} \cdot \begin{bmatrix} v_x(t) \\ v_y(t) \\ \omega(t) \end{bmatrix} \tag{3}$$

To determine the velocity of the robot, the pseudo inverse matrix J_0^+ is determined with the relation [15], [16]:

$$J_0^+ = (J_0^T \cdot J_0)^{-1} J_0^T = \frac{1}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & 1 & -1 \\ -\frac{1}{L+l} & \frac{1}{L+l} & -\frac{1}{L+l} & \frac{1}{L+l} \end{bmatrix} \in R^{3x4} \tag{4}$$

and

$$J_0^T \cdot J_0 = I_3 \tag{5}$$

Using the pseudo inverse matrix J_0^+, we get:

$$\mathrm{V_0} = J_0^+ \cdot \mathrm{V_w} \tag{6}$$

The velocities of the omni-directional robot v_x, v_y and ω_z are given by the following relation [15]:

$$\begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = \mathrm{J^+}_{\mathbf{0}} \begin{bmatrix} V_{1w} \\ V_{2w} \\ V_{3w} \\ V_{4w} \end{bmatrix} \tag{7}$$

or

$$\begin{bmatrix} v_x(t) \\ v_y(t) \\ \omega_z(t) \end{bmatrix} = \frac{R_W}{4} \cdot \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & 1 & -1 \\ -\frac{1}{L+l} & \frac{1}{L+l} & -\frac{1}{L+l} & \frac{1}{L+l} \end{bmatrix} \cdot \begin{bmatrix} \omega_{1w}(t) \\ \omega_{2w}(t) \\ \omega_{3w}(t) \\ \omega_{4w}(t) \end{bmatrix}.$$

(8)

From relation (7) we get:

$$v_x = \frac{R_\omega}{4}\left(\dot{\theta}_{1w} + \dot{\theta}_{2w} + \dot{\theta}_{3w} + \dot{\theta}_{4w}\right) \tag{9}$$

$$v_y = \frac{R_\omega}{4}\left(-\dot{\theta}_{1w} + \dot{\theta}_{2w} + \dot{\theta}_{3w} - \dot{\theta}_{4w}\right) \tag{10}$$

$$\omega_z = \frac{R_\omega}{4(L+l)}\left(-\dot{\theta}_{1w} + \dot{\theta}_{2w} - \dot{\theta}_{3w} + \dot{\theta}_{4w}\right) \quad (11)$$

Where

$$\dot{\theta}_{iw} = \omega_{iw} \ \ (\mathrm{i} = 1, 2\ 3, 4) \quad (12)$$

The omni-directional robot has three degrees of freedom (DOF), only three (v_x, v_y, ω_z) of the four wheel velocities can be assigned independently (ω_{1w}, ω_{2w}, ω_{3w}, ω_{4w}).

The direction of the resultant motion α, is defined by:

$$\alpha = \mathrm{atan}\left(\frac{v_y}{v_x}\right) \quad (13)$$

and resultant velocity with:

$$v_r = \sqrt{v_x^2 + v_y^2} \quad (14)$$

Using the above given equations we can find out the position, direction of motion (13) and resultant velocity (14) of the omni-directional robot with Mecanum wheel.

The inverse kinematic equations allow us to calculate the four independent wheels angular velocities (eq. 3) required to produce a desired robot velocity and rotation.

The forward kinematic equations (9), (10), (11) predict the robot motion, beeing given the four wheel angular velocities.

Another possibility for obtaining the kinematic model is presented in [1], [17], [18], [19], [20].

VII. THE DYNAMIC MODELING

The dynamic model of the omni-directional robot is developed using the Lagrange equation:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_{iw}}\right) - \frac{\partial L}{\partial \theta_{iw}} = \tau_i. \quad (15)$$

The Lagrange equation is based on the Lagrange function and it is defined as the difference between the kinetic energy (K) and the potential energy (U) of the system at a given time:

$$L = K - U \quad (16)$$

in this case, the potential energy U equals zero.

The equation (17) becomes:

$$\frac{d}{dt}\left(\frac{\partial K}{\partial \dot{\theta}_{iw}}\right) - \frac{\partial K}{\partial \theta_{iw}} = \tau_i \quad (17)$$

The kinetic energy K of the robot is determined by the relation [15], [16]:

$$K = \frac{1}{2}m\left(v_x^2 + v_y^2\right) + \frac{1}{2}J_z\omega_z^2 + \frac{1}{2}J_w(\dot{\theta}_{1w}^2 + \dot{\theta}_{2w}^2 + \dot{\theta}_{3w}^2 + \dot{\theta}_{4w}^2) \quad (18)$$

where: m - is the total mass of the robot, J_z - is the robot's moment of inertia around the Z axis, J_w - is the wheel moment of inertia around their centre of revolution, and v_x, v_y, ω_z are the robot speeds, presented above (eq. (9), (10), (11)).

The energy lost due to viscous friction is expressed as:

$$D = \frac{1}{2}D_\theta(\dot{\theta}_{1w}^2 + \dot{\theta}_{2w}^2 + \dot{\theta}_{3w}^2 + \dot{\theta}_{4w}^2) \quad (19)$$

where D_θ is the viscous friction coefficient of the wheels.
Using of the relation (17) and the relations (18), (9)-(11), (19) we get:

$$\tau = \mathrm{M}\ddot{\theta}_w + D_\theta\dot{\theta}_w \quad (20)$$

where:

$\theta_w = [\theta_{1w}\ \ \theta_{2w}\ \ \theta_{3w}\ \ \theta_{4w}]^T$ is the rotation angle of the wheel,

$\tau = [\tau_1\ \ \tau_2\ \ \tau_3\ \ \tau_4]^T$ is the driving torque acting on which wheel.

In the equation (20) the following annotations were used [15], [16]

$$\mathrm{M} = \begin{bmatrix} A_J + B_J + J_w & -B_J & B_J & A_J - B_J \\ -B_J & A_J + B_J + J_w & A_J - B_J & B_J \\ B_J & A_J - B_J & A_J + B_J + J_w & -B_J \\ A_J - B_J & B_J & -B_J & A_J + B_J + J_w \end{bmatrix} \quad (21)$$

where

$$A_J = \frac{m \cdot {R_w}^2}{8} \quad (22)$$

$$B_J = \frac{J_z \cdot {R_w}^2}{16(L+l)^2} \quad (23)$$

Another possibility for obtaining the dynamic model is presented in [19].

VIII. THE TESTING AND DISCUTION

This paper is the result of a research session conducted in the Robotics Laboratory of the Faculty of Mechanical Engineering within the Technical University of Cluj-Napoca, Romania.

Contributions of authors presented in this paper are mainly omni-directional wheel design and hardware structure of the omnidirectional robot.

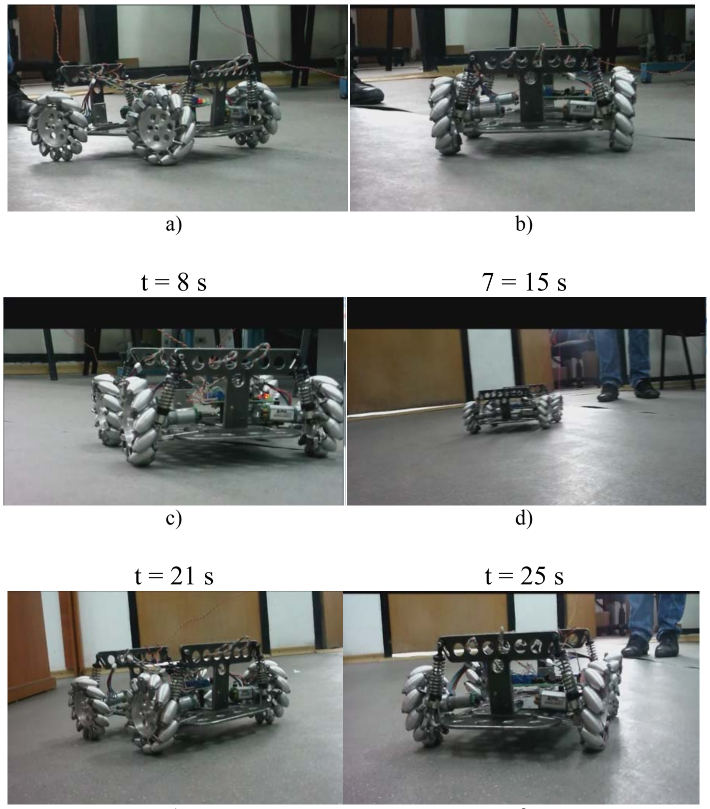
Compared to other mobile robots, proposed suspension system enables omni-directional robot displacement on surfaces with small bumps. Kinematics and dynamics modeling is useful for robot control.

The developed omni-directional robot has the following characteristics: mass /weight about 2 [kg], height 140 [mm], length 290 [mm], width 270 [mm].

The testing process of the omni-directional robot was successfully carried out in laboratory conditions yielding good results.

It is worth mentioning that, in the case of locomotion on low friction surfaces (eg. plastic surfaces, surfaces covered with oil), robot slip and can not be controlled effectively.

Some images, taken during the testing process, are presented below (Fig. 10).



t = 0 s t = 2 s

a) b)

t = 8 s 7 = 15 s

c) d)

t = 21 s t = 25 s

e) f)

Figure 10. The testing of the omnidirectional robot

Future work:

The omni-directional robot will be equipped with a gripper for handling small objects, a video camera and sensors for avoiding obstacles. Another objective is to improve the omnidirectional wheel design that is used in the current model.

Also, equipping the omni-directional mobile robot with batteries in order to achieve its energetic autonomy is another objective that the research team has in view.

IX. CONCLUSION

The Mecanum wheels present a number of advantages, that makes them a real interest in development of the omni-directional platforms. Due to its capabilities, the omni-directional robot presented in this paper, can be used as a platform for education and research.

REFERENCES

[1] P. Muir, C. Neuman “Kinematic modeling for feedback control of an omnidirectional wheeled mobile robot”, Proceedings, IEEE International Conference in Robotics and Automation, Vol 4. pp. 1772-1778, 1987.

[2] J.B. Song, K.S. Byun, “Design and Control of a Four-Wheeled Omnidirectional Mobile Robot with Steerable Omnidirectional Wheels”, Journal of Robotic Systems, Vol. 21, No.4 (2004), pp. 193-208.

[3] I. Doroftei, V. Grosu, V. Spinu, “Omnidirectional Mobile Robot - Design and Implementation”, Book-Chapter, Bioinspiration and Robotics - Climbing and Walking Robots, Editor Maki K. Habib, Published by Advanced Robotic Systems International (Vienna) and I-Tech, 2007, pp. 511-529.

[4] L.C. Lin, H.Y. Shih “Modeling and Adaptive Control of an Omni-Mecanum-Wheeled Robot” Intelligent Control and Automation, 4 (2013), pp. 166-179.

[5] K.L. Han, H. Kim, J. S. Lee “The Sources of Position Errors of Omni-directional Mobile Robot with Mecanum Wheel”, Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 2010, pp. 581-586.

[6] K.-L. Han, O. K. Choi, I. Lee, I. Hwang, J. S. Lee, S. Choi “Design and Control of Omni-Directional Mobile Robot for Mobile Haptic Interface“, International Conference on Control, Automation and Systems 2008, Oct. 14-17, 2008 in COEX, Seoul, Korea, pp.1290-1295.

[7] I. Doroftei, B. Stirbu, “Design, Modeling and Control of an Omni-directional Mobile Robot”, Solid State Phenomena Vols. 166-167, (2010), pp. 173-178.

[8] T. Braunl, “Embedded Robotics: Mobile Robot Design and Applications with Embedded Systems”, First Edition. Springer-Verlag, Berlin, 2003, pp. 113-121.

[9] F. Adascalitei, I. Doroftei, “Practical Applications for Mobile Robots based on Mecanum Wheels - a Systematic Survey”, Proceedings of International Conference On Innovations, Recent Trends And Challenges In Mechatronics,Mechanical Engineering And New High-Tech Products Development – MECAHITECH’11, Vol. 3, 2011, pp. 112-123.

[10] P.J. Mc Kerrow “Introduction to Robotics“, Adison - Wessley Co, 1991.

[11] A. Ramirez-Serrano, R. Kuzyk, “Modified Mecanum Wheels for Traversing Rough Terrains”, Sixth International Conference on Autonomic and Autonomous Systems, ICAS 2010, Cancun, Mexico, 2010. pp. 97-103.

[12] O. Diegel, A. Badve, G. Bright J. Potgieter S. Tlale, “Improved Mecanum Wheel Design for Omnidirectional Robots“, Proceedings of the Australasian Conference on Robotics and Automation, Auckland, 27-29 November, 2002, pp. 117-122.

[13] C.V. Popovici, M.O. Tătar, C. Cirebea, “Development of an omnidirectional robot with mecanum wheels”, *Robotica & Management, 2012,* Vol. 17, No. 1, June, (2012), pp. 37-40.

[14] M.O. Tătar, C. Cirebea D. Mândru, “Structures of the Omnidirectional Robots with Swedish Wheels”, Solid State Phenomena, Vol. 198, Mechatronic Systems and Materials IV, (2013), pp. 132-137.

[15] P. Viboonchaicheep, A. Shimada, Y. Kosaka, “Position Rectification Control for Mecanum Wheeled Omni-directional Vehicles”, Proceedings the 29th Annual Conference of the IEEE Industrial Electronics Society, Roanoke, VA, USA, 2003, pp. 854-859.

[16] A. Shimada, S.Yajima, P.Viboonchaicheep, K. Samura “Mecanum-wheel vehicle systems based on position corrective control” in 32nd Annual Conference of IEEE Industrial Electronics Society, 2005, pp. 2077-2082, available from: IEEE Xplore.

[17] G. Campion, G. Bastin, B., Andrea-Novel, “Structural Properties and Classification of Kinematic and Dynamic Models of Wheeled Mobile Robots”, IEEE Transactions on Robotics and Automation, Vol 12, No. 1, 1996.

[18] R. Siegwart, I.,Nourbackhsh, “Introduction to Autonomous Mobile Robots”, The MIT Press, Massachsetts, 2004.

[19] N. Tlale, M.Villiers, “Kinematics and Dynamics Modelling of a Mecanum“, Wheeled Mobile Platform, 15th International Conference on Mechatronics and Machine Visionin Practice (M2VIP08), 2-4 Dec 2008, Auckland, New-Zealand, pp. 657-662.

[20] S. G. Tzafestas “Introduction to Mobile Robot Control“ Elsevier, 2013.