Simplified Mecanum Wheel Modelling using a Reduced Omni Wheel Model for Dynamic Simulation of an Omnidirectional Mobile Robot

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Abstract—**Industrial and technical applications of omnidirectional mobile robots, with Mecanum wheels, are continuously gaining in importance because their excellent mobility, especially in areas with static or dynamic obstacles. The perspective of Industry 4.0 imposes an effective and efficient approach for production in general and then, specific to this application, to implement the control algorithm able to deliver to robot the deliberatively and reactively behaviour. An important tool to achieve these goals is virtualization of the prototype and his simulation in a 3D virtual environment.**

This paper presents a simplified method of modelling and kinematics simulation in Simscape Multibody™, taking an omnidirectional mobile robot with advantages related to simulation time. The necessary steps to develop inverse kinematics in robots and global reference frame, for specific omnidirectional mobile robot, are depicted in the paper using bottom-up approach with matrix transformation. The 3D modelling process starts from the CAD design, which is then transferred into a Simscape Multibody™ model in order to study the kinematic and dynamic characteristics. Four typical motion models including moving forward, moving laterally, moving in the diagonal direction and rotation have been simulated in Simscape Multibody™.

Keywords— omnidirectional mobile robot; kinematics; virtual prototype; Mecanum wheels; simulation; Simscape-Multibody.

I. Introduction

In the last decade, autonomous systems have become quite a popular topic for collaboration between several research academic groups and industry. Autonomous systems are complex structures being a multidisciplinary approach of various engineering and science disciplines, from mechanical, electrical and electronics engineering to computer, cognitive and social sciences. An important direction of this domain is represented by autonomous mobile robots (AMRs), defined in [1] as a system which operates with a various degree of autonomy in order to perform a goal-oriented. AMRs are highly versatile systems with the capability to take decisions in order to solve the complex tasks through two types of approaches: deliberately and reactively. Acting deliberately means the AMR requires relatively complete knowledge of the operating space and uses it to plan its subsequent actions. On the other hand, reactive actuation is based on techniques for tightly coupling information from the environment and the robot's drive system so that for a displacement in a dynamic or unstructured operating environment it can have a real-time response [2].

Based on diversity of operational environments that they have to operate, the AMRs can be classified into unmanned ground vehicles (UGVs), unmanned water vehicles (UWVs), autonomous underwater vehicles (AUVs), and unmanned aerial vehicles (UAVs). The research presented in this paper is related to a subclass of UGVs, which is using Mecanum wheels. The main strength of the use of this omnidirectional locomotion in UGV applications is due to the ability of these wheels to move instantaneously in any direction, gaining advantages in terms of their manoeuvrability and productivity in narrow spaces and/or crowded environments [3]. This is possible because translational and rotational motions can be decoupled for vehicle displacement. Typical applications for omnidirectional mobile robots (OMRs) are from different fields, as they are presented in [4], such as military applications, plant work-shops, logistics spaces, offices and care facilities like hospitals.

The paper is organized as follows. Section II explains the kinematic model of an OMR with 4 Mecanum wheels. Section III presents the 3D CAD model of the robot which is available at the Department of Automatic Control and Applied Informatics – TUIASI. In section IV the translation of obtained OMR's model in Simscape Multibody™ is presented. The main contribution of this paper, presented in section V, is a proposal of a simplified equivalent model for the 4 Mecanum wheeled platform, based on the behaviour of the 4 Omni wheeled platform. The proposed simplified model is less time consuming and it can guarantee acceptable kinematic and dynamic accuracy. The model behaviour and comparative analyses are presented in section VI. Section VII presents the conclusions.

II. Kinematic Model

In this section, the kinematics of an omnidirectional mobile platform with 4 Mecanum wheels is depicted. Kinematics study offers the possibility to analyse the geometry of motion

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for OMR. On the other hand, in order to control its manoeuvrability one has to use associated inverse kinematics.

A. Mecanum Wheels

Mecanum wheel is based on the principle of a central hub with several rollers placed at an angle around the periphery of the hub. The angle between rollers axes and central hub axis could have any value, but in the case of conventional Mecanum wheel it is 45°. The OMR kinematic model is presented in the technical literature [3],[5]-[7] like a typical bottom-up approach: the first step starts with constraints on the motion of individual wheel, and then, by combining the motion of used wheels the behaviour of the designed robot as a whole can be obtained [1]. In order to simplify the model, there are defined some ideal conditions of operating Mecanum wheel in a 2D plane [8] and construction conditions of wheel/chassis. Two common methods to develop the kinematic constraints of a Mecanum wheel are used: one based on vector method and the other characterised by using the matrix transformation. Our approach is the second one, and for this purpose we will define the following Cartesian coordinates systems and configuration parameters:

- $O_{wi}X_{wi}Y_{wi}Z_{wi}$ - the system attached to wheel w_i;
- $o_i x_i y_i z_i$ - the system attached to the roller in contact to the ground;
- OXYZ - the local systems attached to robot base chassis;
- $O^G X^G Y^G Z^G$ - the global world reference frame;
- R – wheel radius;
- (l_i, α_i) – defines the position of wheel w_i towards the kinematic centre of chassis O, $|l_i| = \text{dist.}(O_{wi}\,O)$;
- β_i, γ_i - the angle between direction of vector l_i and X_{wi} axis of the wheel, the tilt angle between axes x_i and X_{wi} projection respectively;
- θ - rotational angle of the robot around Z_R axis;
- ω_i, Ω - angular velocity of the wheel w_i, angular velocity of the robot, respectively ($\Omega = \dot{\theta}$)
- v_x, v_y - the instantaneous translation velocities of the robot in its coordinated axes;
- v_x^G, v_y^G, Ω^G - the instantaneous velocities of the robot in global reference frame;
- v_{gi} - the velocity of roller in contact with the ground from wheel w_i;
- l_x, l_y - half of the distance between the front wheels contact points, half of the distance between the front and the rear wheels contact points;

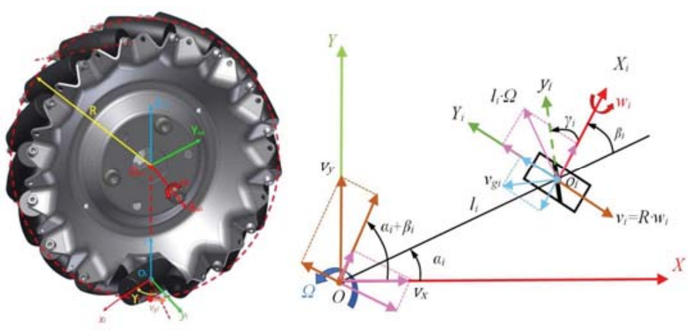

Fig. 1. Coordinate systems attached to Mecanum wheel w_i and kinematic constraint diagram of its using a matrix transformation method.

All conventions in Fig.1 respect right-handed Cartesians coordinate system. In representation of the wheel in OXY plane everything should be judged in terms of wheel tracks left on ground.

The matrix transformation method is the most used method for kinematics constraints analysing of a wheeled mobile system. The calculation is based on the study of rolling and sliding constraints of the Mecanum wheel which requires some subtlety: in order to obtain movement, the contact point between wheel and ground is a pure rolling condition without slipping [9].

B. Inverse Kinematics

Performing translation and rotation of velocity of the coordinate frame of the wheel w_i to instantaneous velocities of the robot, the following relations result [6], [10]:

$$v_x \sin(\alpha_i+\beta_i) - v_y \cos(\alpha_i+\beta_i) - l_i\Omega\cos\beta_i = R\omega_i - v_{gi}\cos\gamma_i \tag{1}$$

$$v_x \cos(\alpha_i+\beta_i) + v_y \sin(\alpha_i+\beta_i) + l_i\Omega\sin\beta_i = \quad - v_{gi}\cos\gamma_i \tag{2}$$

Being an uncontrollable variable of the passive roller, the velocity v_{gi} must be eliminated from above equations. In this way, from eqs (1)-(2) it results

$$v_x \cos(\alpha_i+\beta_i+\gamma_i) + v_y \sin(\alpha_i+\beta_i+\gamma_i) + l_i\Omega\sin(\beta_i+\gamma_i) = -R\omega_i\sin\gamma_i \tag{3}$$

By introducing the vector of robot velocities $\dot{\zeta} = [v_x\ v_y\ \Omega]^T$ in eq. (3), the wheel speed ω_i can be expressed as

$$\omega_i = -\frac{1}{R\sin\gamma_i}[\cos(\alpha_i+\beta_i+\gamma_i)\ \ \sin(\alpha_i+\beta_i+\gamma_i)\ \ l_i\sin(\beta_i+\gamma_i)]\,\dot{\zeta} \tag{4}$$

Because it is taken into consideration an OMR with four Mecanum wheels in optimal configuration, the wheels are in a symmetrical arrangement with axes of rollers in "square" layout – Fig. 2, and rollers angle values for each wheel are presented in Table I.

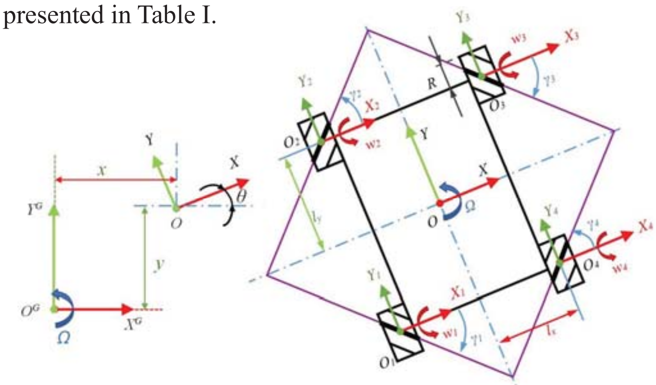

Fig. 2. Coordinates system assignments for the four-Mecanum-wheel robot with arrangement of rollers in "square" layout.

Table I Roller angle values for wheel w_i

Index i	1	2	3	4
γ_i	-45°	45°	-45°	45°

Specific for this kind of wheels distribution is that the sum of angle α_i and angle β_i is null, i.e.

$$\alpha_i = -\beta_i \tag{5}$$

and, for this case, eq. (4) can be rewritten as:

$$\omega_i = -\frac{1}{R}\left[\frac{\cos\gamma_i}{\sin\gamma_i}\ \ 1\ \ l_i\frac{\sin(-\alpha_i+\gamma_i)}{\sin\gamma_i}\right][v_x\ v_y\ \Omega]^T \tag{6}$$

From constructive dimensions of chassis one obtains $l_x = l_i\cos\alpha_i$, $l_y = l_i\sin\alpha_i$ and hence eq. (6) becomes:

$$\omega_i = -\frac{1}{R}\left[ctg\gamma_i \;\; 1 \;\; l_x - l_y ctg\gamma_i\right][v_x \; v_y \; \Omega]^T \tag{7}$$

Taking into consideration the value of rollers angle for each wheel and the sign of chassis dimensions, by using eq.(7) four times one obtains the inverse kinematics matrix of the OMR, which relates the angular velocities of the Mecanum wheels to the velocities coordinates of robot as follow:

$$\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\\ \omega_4\end{bmatrix} = -\frac{1}{R}\begin{bmatrix}-1 & 1 & -(l_x+l_y)\\ 1 & 1 & -(l_x+l_y)\\ -1 & 1 & (l_x+l_y)\\ 1 & 1 & (l_x+l_y)\end{bmatrix}\begin{bmatrix}v_x\\ v_y\\ \Omega\end{bmatrix} \tag{8}$$

The angular velocities of the Mecanum wheels can be related to the velocities in global coordinates by using the *orthogonal rotation matrix, denoted by*:

$$R_{rot}(\theta) = \begin{bmatrix}\cos\theta & \sin\theta & 0\\ -\sin\theta & \cos\theta & 0\\ 0 & 0 & 1\end{bmatrix} \tag{9}$$

Considering that the vector of robot velocities can be expressed as

$$\dot{\zeta} = R_{rot}(\theta)\,\dot{\zeta}^G \tag{10}$$

then the inverse kinematic equation (8) in global reference frame $O^GX^GY^GZ^G$ becomes:

$$\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\\ \omega_4\end{bmatrix} = -\frac{1}{R}\begin{bmatrix}-1 & 1 & -(l_x+l_y)\\ 1 & 1 & -(l_x+l_y)\\ -1 & 1 & (l_x+l_y)\\ 1 & 1 & (l_x+l_y)\end{bmatrix}\begin{bmatrix}\cos\theta & \sin\theta & 0\\ -\sin\theta & \cos\theta & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}v_x^G\\ v_y^G\\ \Omega^G\end{bmatrix} \tag{11}$$

Inverse kinematics is essentially in creating a kinematic chain when the mobile robot is modelled with a chassis compound of rigid segments connected with joints. More than this, with inverse kinematics problem, the joint angles for a desired position of the platform may be computed, which is useful in following a robot trajectory when the controller calculates the translational and angular velocities.

The inverse Jacobian matrix of the OMR is

$$J = -\frac{1}{R}\begin{bmatrix}-1 & 1 & -(l_x+l_y)\\ 1 & 1 & -(l_x+l_y)\\ -1 & 1 & (l_x+l_y)\\ 1 & 1 & (l_x+l_y)\end{bmatrix} \tag{12}$$

Equation (12) shows that for the OMR with more than 3 Mecanum wheels, the kinematics is over-determined i.e. only three rows of the Jacobian matrix are linear independent, the fourth one being a linear combination of the first three.

C. Forward Kinematics

The approach which starts with wheels velocities in order to determinate the platform velocities is known as forward kinematics. In order to obtain the forward kinematic equations starting from Jacobian matrix, which is a 4x3 matrix, it is necessary to introduce a pseudo inverse matrix J^+ such that $J^+ \cdot J = I_3$. It is determined with the formula [7]:

$$J^+ = (J^T \cdot J)^{-1} \cdot J^T \tag{13}$$

In this way one can obtain the equation for forward kinematics as following:

$$\begin{bmatrix}v_x\\ v_y\\ \Omega\end{bmatrix} = -\frac{R}{4}\begin{bmatrix}-1 & 1 & -1 & 1\\ 1 & 1 & 1 & 1\\ -\frac{1}{l_x+l_y} & -\frac{1}{l_x+l_y} & \frac{1}{l_x+l_y} & \frac{1}{l_x+l_y}\end{bmatrix}\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\\ \omega_4\end{bmatrix} \tag{14}$$

Equation (14) shows the three degrees of freedom (3DoF) of the platform: two translational velocities on X and Y axes and one angular speed around Z axis. The resultant translational velocity is defined by:

$$v = \sqrt{v_x^2 + v_y^2} \tag{15}$$

and orientation is calculated as:

$$\theta = \tan^{-1}\frac{v_y}{v_x} \tag{16}$$

From forward kinematics given by (14) the OMR can be driven in every direction according to the direction and angular speed of the wheels:

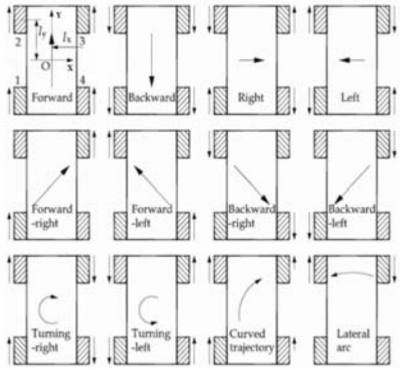

Fig. 3. Locomotion directions according with angular velocity of the wheels [4].

The figured arrows attached to the wheels take into account the (-) sign of Jacobian matrix and that resulted from right-handed Cartesians coordinate system for angular velocities.

III. Designing the Model in 3D CAD

In last decade when the fourth industrial revolution imposed proper paradigms, the virtual prototyping started to have the biggest impact in an integrated concept of preparing physical prototypes. Advantages brought by modelling, testing, measurements in the virtual environment are transposed in real environment by production cost savings, reduced testing and optimization time, tests without destroying prototypes, increase of quality (operational performances) of the products. In [10] virtual prototyping is defined as a computer-aided engineering-based discipline. The starting point for such system is high-performance 3D CAD software.

In order to study the kinematic and dynamic characteristics for the ORM, the 3D CAD model was designed using Autodesk-Inventor software and virtual prototype simulations were carried out in Simscape Multibody™ to simulate and optimize its behaviour. Even though it is possible to develop models directly in Simscape Multibody™, specialized tools offered by high-performance CAD software give the possibility to create more sophisticated 3D geometrical model in order to obtain all the mass and inertia properties.

The real OMR and the model of OMR designed in Autodesk Inventor with all details are presented in Fig. 4.

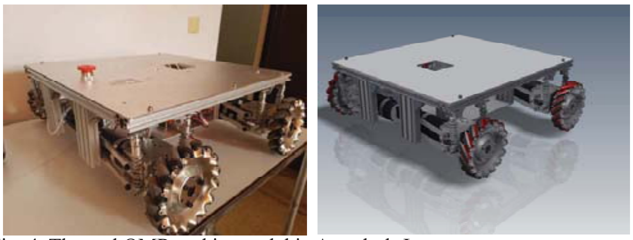

Fig. 4. The real OMR and its model in Autodesk-Inventor.

Before being exported to Simscape Multibody™, the model should be simplified, to diminish the amount of data processing and to increase the efficiency of simulation time. For this purpose it is necessary to retain only the main components with big impact in simulation: four Mecanum wheels, four motor-gearbox assemblies, eight shock absorbers, eight parallelogram mechanisms and the main body of platform, which freeze all other components with less impact in simulation (battery, control/communications equipment and other mechanical components). Reducing texture of the materials can also affect the performance in simulation.

The simplified model, Fig. 5, contains all details with impact in model dynamics.

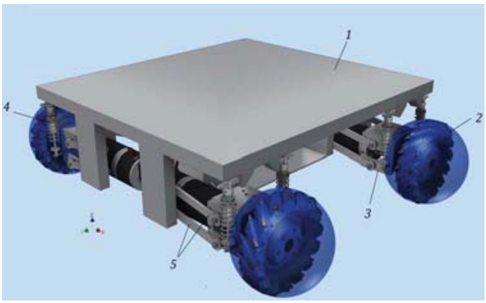

Fig. 5. Reduced 3D model of the OMR in Autodesk-Inventor with 1-rigid body, 2-Mecanum wheel and circumscribed sphere, 3- motor-planetary gearbox assembly, 4-shock absorber, 5-parallelogram mechanisms.

Table II presents some characteristics and dimensions of real OMR embedded in simplified model from Inventor.

Table II Dimensions of real OMR

Parameter (symbol)	**Value**	**Unit**
Distance l_x	0.294	[m]
Distance l_y	0.200	[m]
OMR weight	14.5	[kg]
Wheel radius (R)	0.076	[m]
#of rollers/wheel	16	

In order to prevent errors when importing the model it is necessary to make sure that in CAD assembly model the constraint combination between bodies are correctly defined, otherwise unsupported constraint combinations between bodies will be replaced in Simscape Multibody™ by a rigid connection, in one of the forms: direct frame connection line, Rigid Transform block or Weld Joint block. Reference [11] presents all translation processes of a CAD model into a Simscape Multibody™ - Simulink model. This process is done in 2 steps. First, the CAD export procedure creates an Extensible Markup Language (*xml*) multibody description file, and then a set of geometry files with extension *STEP* which provides the 3D surface shapes of the CAD parts.

IV. The OMR Dynamic Simscape Multibody Model

The procedure to obtain a dynamic model for a complex mechatronic system, as it is the OMR, is a confortable way which makes Simscape Multibody™ a powerful and friendly tool for manipulation of a 3D virtual prototyping. The simulation of the model can be done either when the system is going to be built, or if it already exists and it is necessary to develop control system – the case of preparing the prototype in the current research project.

The results derived from importing CAD model are a Simscape Multibody™-Simulink model (extension *slx*) of OMR and an *m* data file. The data from *m* file sets the block parameter values of the imported Simscape-Multibody™ model. The translated model keeps the structural hierarchy from the CAD assembly.

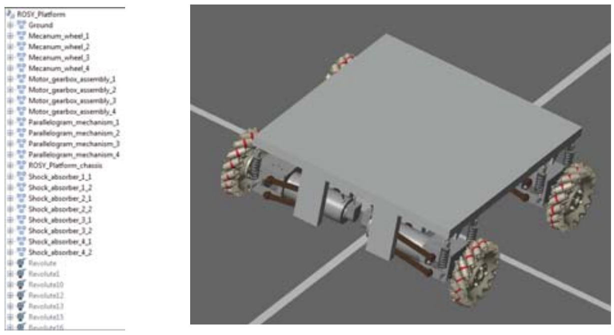

Fig. 6. Structure of the OMR Simscape-Multibody™ model with main components.

The Simscape Multibody™ model is represented as combinations of joints and constraints blocks. After processing and rearranging the blocks, the resulting model is presented in Fig.7, where the main blocks are highlighted in the form of subsystems in which the component elements have been grouped.

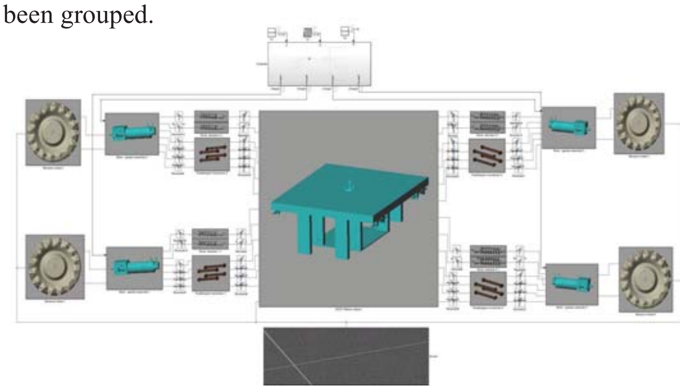

Fig. 7. The OMR Simscape Multibody™ model.

In order to obtain a realistic model for the Mecanum wheels that could also be simulated using Simscape Multibody™, the 16 rollers were approximated using 16 spheres having the same radii as the rollers. Each sphere is attached to the circumference of the wheel using a separate non-actuated revolute joint to provide the needed rotational DOFs, similar to the work presented in [12]. Furthermore, the interaction of each simplified roller with the ground surface is modelled with instances of the standard sphere to plane contact model from Contact Forces Library (CFL) extension of Simscape Multibody™. The modelled contact spheres are partially visible in Fig. 6 represented as red rings on the centre of each roller.

Obviously, the approximation of the original rollers with spheres causes a non-uniform transition between two consecutive rollers that creates vibrations in the OMR body. While this may seem like a discrepancy compared to the ideal Mecanum wheel, it can also reflect the behaviour of some real wheels which due to their particular manufacture may produce a similar effect although attenuated. Such a transition vibration was observed also for the wheels of the experimental OMR used in the current research.

An important downside of the above model is the slow simulation speed, issue that motivated further research into a simplified equivalent dynamic model.

V. Mecanum Wheel Modelling using Reduced Omni Wheel Model

In order to accelerate the simulation, the Mecanum wheel can be considered as a source of force in the direction of the rotation axis of the roller in contact with the ground surface. Starting from this, it is of interest to develop a simulation model that achieves similar dynamic characteristics to a Mecanum wheel while unburdening the computational complexity.

The simplest apparent solution is to model the Mecanum wheel as a sphere of the same radius, sphere which would be torque actuated on one horizontal axis, optionally immobilized on the vertical rotation axis (since rotation of the sphere around the vertical axis would not produce translation motion, nor the original rollers have this degree of freedom) and also allowed to rotate freely around the last remaining orthogonal horizontal axis, as the rollers do.

Such a model can be implemented in Simulink using two components from Simscape Multibody™: a sphere to plan contact model from CFL and a spherical joint which is closed loop torque actuated on two of the orthogonal rotational axis by sensing the orthogonal angular speeds as illustrated in Fig. 8.

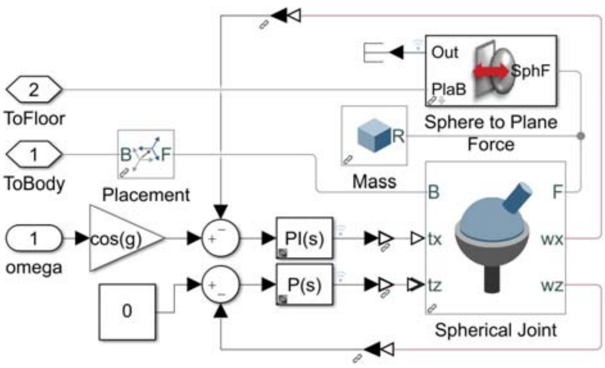

Fig. 8. Simplified model for Mecanum wheel implemented in Simscape Multibody™ by equivalence with a reduced Omni wheel.

One of the torques can be controlled by a PI controller to compensate the angular velocity error between the desired wheel angular velocity and the actual angular velocity, while for immobilizing the rotation around the vertical axis (which can be helpful while inspecting the dynamics of the model) a simple P controller with constant reference speed set to zero would suffice.

The proposed model represents a reduced Omni wheel (an omnidirectional wheel for which $|\gamma_i| = 90°$), Fig.9.

		Mecanum	Omni
Kinematics	forward – v_f	$\omega \cdot R$	$\omega \cdot R\sqrt{2}$
	sideways - v_s	$\omega \cdot R$	$\omega \cdot R\sqrt{2}$
	diagonal - v_d	$\omega \cdot R / \sqrt{2}$	$\omega \cdot R$
Force	forward – F_f	$4\tau / R$	$4\tau / (R\sqrt{2})$
	sideways - F_s	$4\tau / R$	$4\tau / (R\sqrt{2})$
	diagonal - F_d	$2\tau\sqrt{2} / R$	$2\tau / R$

Fig. 9. Comparison based on velocity and pushing force.

The two columns in Fig. 9 summarize the ground velocities and traction forces for vehicles with four wheels of type Mecanum and Omni respectively, considering they have the same diameter. The first three rows are vehicle velocity: forward, sideways and diagonal, for a given wheel speed ω. The second three rows are vehicle total pushing force: forward, sideways and diagonal, for a given wheel torque τ [13].

The model is described as reduced because in simulation a single sphere can be used to produce traction in one direction and allow free rolling on the perpendicular direction, while in practice several rollers along the circumference of the wheel are required. The usage of an Omni wheel model requires two adjustments in order to maintain the equivalence with the Mecanum wheel from the point of view of inverse kinematics matrix [13].

The first is to rotate in place each wheel with γ_i around the vertical axis so that traction force is produced along the free rotation axis of the Mecanum roller in contact with the ground,

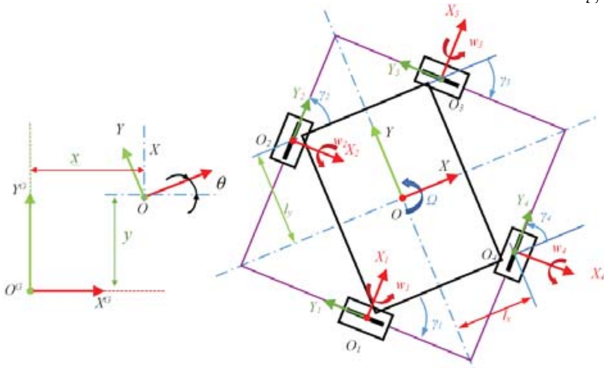

Fig. 10. OMR using the equivalent Omni wheels topology.

The second adjustment is a consequence of the γ_i rotation and requires the scaling of the reference actuation speeds ω_i by a factor of $cos\gamma_i$ (γ_i=45°). Practically for the Omni wheel model the vehicle's Jacobian is given by (17).

$$J = -\frac{\sqrt{2}}{2R}\begin{bmatrix} -1 & 1 & -(l_x + l_y) \\ 1 & 1 & -(l_x + l_y) \\ -1 & 1 & (l_x + l_y) \\ 1 & 1 & (l_x + l_y) \end{bmatrix} \tag{17}$$

VI. EXPERIMENTAL RESULTS

In order to validate the complete model dynamics and to investigate the response of the two wheel models, a 10s long test case involving four relevant movements depicted in Fig 11. The ground speed references are provided, and each wheel angular velocity is controlled according to the inverse kinematics equations. The open loop ground speeds are then observed and represented against the reference speeds as illustrated in Fig. 12 for the equivalent model using reduced Omni wheels. The test case starts with a 0.2s settling time so that the model suspensions reach equilibrium, then it follows a translation along X axis, a stop, a translation along Y axis, another stop, a translation along the main diagonal towards origin, one more stop and finally a 180° turn and a final stop. The target translation speed on each axis is 1m/s achieved with a reference acceleration of 2.5m/s^2. The target angular velocity is 1rad/s and the angular acceleration is limited at 2π rad/s^2.

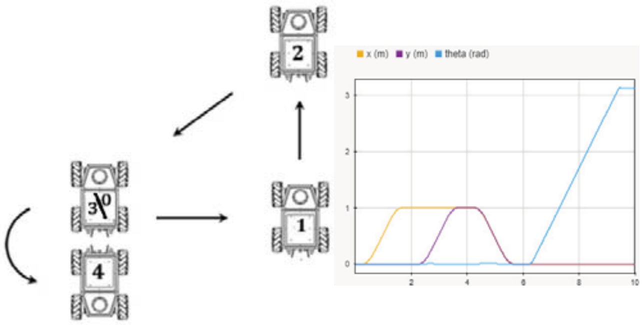

Fig. 11. The schematic map for robot navigation (left) and displacement on global world reference frame (right).

From the point of view of the simulation efficiency, the simplified model using reduced Omni wheels (against Mecanum wheel modelled with 16 spheres) performed about 10 times faster for the test case (330s/3465s) while maintaining all other components and simulation parameters the same. The simulations run on high performance Asus ROG Strix G732LXS graphics system based on Intel i9 10th generation 10980HK 8 core x 2 logical processors CPU @3.1GHz up to 5.1GHz with NVIDIA GeForce RTX 2080 Super 8GB dedicated VRAM.

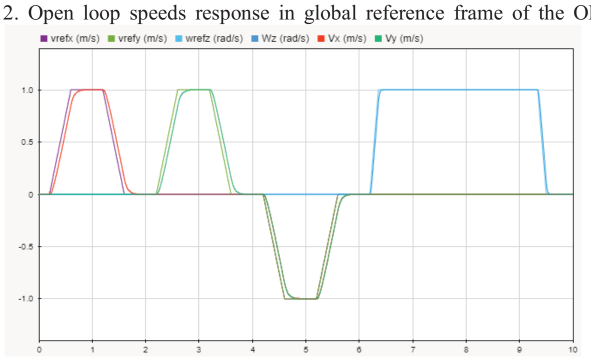

Fig. 12. Open loop speeds response in global reference frame of the OMR using the simplified model based on reduced Omni wheels.

The simulation results validate the proposed simplified model of OMR based on reduced Omni wheels.

VII. CONCLUSION AND FUTURE WORK

The research of the authors is focused on obtaining a simplified Mecanum wheel model and using the bottom-up method to build and simulate the virtual prototype of an omnidirectional mobile robot in Simscape Multibody™ in order to study its kinematic/dynamic behaviour. Analyses in this environment use all facilities given by integration of all Matlab toolboxes. In simulation process, time is a critical resource even on performant systems for complex models, as an OMR, and saving time with this simplified model offers real benefits in entire process of analyses. The modelling process is presented by main milestones among which the representation of contact forces, this plays a key role in analysis of an OMR dynamics.

The simulation results can be used for further dimensioning and optimizations of OMR and not in the least to test different control strategies.

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