State space model of an omni-directional holonomic mobile robot

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Abstract

In this paper a mathematical model is presented for an omni-directional holonomic mobile robot equipped with 3 omni-wheels. This model takes all the dynamics of the robot into account and uses the state space method. The intention of creating such a model is because of the deficiency of the mobile robotics literature. Mainly the kinematics or inverse kinematics of a holonomic mobile robot is commonly discussed. Further use of this model is in the mechatronics education and in the research field of eto-robotics. With the exact aim of teaching and learning advanced control methods, which are requiring the mathematical model of the system to be controlled. Simulations were carried out to validate the model. Although results of the preliminary analysis have validated our model it is planned in the near future to implement the model and an adequate control algorithm at first to control the position in a known space (i.e. room) of a real life mobile robot.

1. Introduction [3-7]

In this paper a mathematical model is presented for an omni-directional holonomic mobile robot equipped with 3 omnidirectional wheels. This model takes the dynamics of the robot into account and uses the state space method.

The intention of creating this model is to further improve the mobile robotics literature. Furthermore open discussion about how to improve these vehicles and use them as state-of-the-art tools in the robotics education.

One particular field of use is eto-robotics. Where ethologically inspired mobile robots are created and constantly investigated by researchers from robotics, mechatronics, biology and ethology. These robots also featuring omni-directional drive train [2].

Last but not least the industrial applications of these autonomous and not autonomous vehicles are rare. Whit the application of a good dynamical model and advanced control algorithms omni-directional robots and forklifts can be implemented in the near future.

The subject of the investigation is an omni-directional mobile robot equipped with 3 omni-wheels. The Robotino® has been chosen for this purpose. In the next section a brief introduction will follow about this robot

1.1. The Festo Robotino®

The Festo Robotino® is an omni-directional mobile robot equipped with 3 omni-wheels and designed for education. (Figure 1)

Figure 1. The Festo Robotino®

In this paper just drive train and the mechanical assembly of the Robotino® is considered. A complete introduction of the robot can be found in [1].

In Figure 2 one driving block of the Robotino® can be seen. This block consists of a 24 V DC motor, an incremental encoder, toothed belt and a gear unit (resultant gear ratio: 16:1) and finally an all-way-roller also called omni-directional wheel. The wheel is a common wheel equipped with a number of free running rollers on the wheel's outer edge.

In this paper for the formulation of the relationship between wheel speeds and robot speed the gear ratio isn't regarded, because isn't affecting the form of the equations just the numeric values; what will be regarded during the numerical simulation and implementation of the model in the near future.

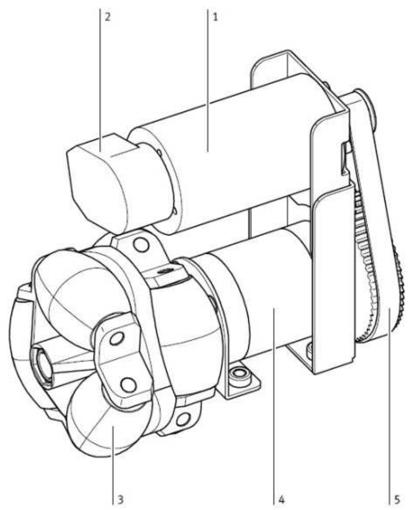

Figure 2. Driving block of the Robotino®. (1): Motor, (2): Incremental encoder, (3): Omni-wheel, (4): Gear unit, (5): Toothed belt. [10]

Figure 3 is showing the arrangement of the above mentioned driving blocks. There are 3 driving blocks in the robot. All equally spaced by 120° about the robot's center point. On Figure 3 the driving blocks are noted as M1, M2, M3.

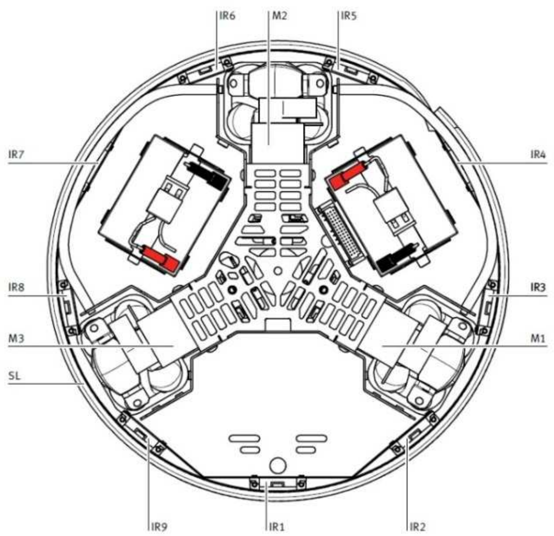

Figure 3. Drive train assembly of the Robotino®. M1 to M3: motors. [10]

2. Developing the State Space model

In this section the State Space model of the holonomic drive is pursued. Although the kinematic model of a holonomic drive train can be found it is better to develop our own kinematic model to be consistent with the dynamics.

At the first approximation some assumptions were made regarding the mechanical construction of the robot. Regarding the driving blocks only the wheel speeds and inertias have been taken into account. All masses and inertias are considered as parts of the wheel mass and inertia. The gear ratio between the motor and the wheel has been also disregarded.

The Omni-wheel itself is treated as one solid body whit the ability to produce tractive effort on the ground without slipping. This corresponds to the rolling constraint in case of a traditional wheel. On the other hand the center point of the wheel could have an axial velocity which is produced by the other two wheels at any time. The axial velocity of the wheel's center of mass is because of the free running rollers. The rollers' rolling directions are parallel to the wheel's shaft (see Figure 2.).

Regarding the drive train assembly it is assumed that the axes of the wheel shafts are intersecting in one point and one point only and this point is the robot's center of mass. (see Figure 3.).

2.1. Kinematics of the holonomic drive[8]

The aim of this section is to develop the relationship between the wheel speeds and the vehicle speeds. In order to derive this relationship, the following assumptions were made:

- Each wheel contacts the ground at a single point.
- All of the wheels roll on the ground without slipping.

First a coordinate system ($\mathcal{F}_1\{n_1, t_1, b_1\}$, $\mathcal{F}_2\{n_2, t_2, b_2\}$, $\mathcal{F}_3\{n_3, t_3, b_3\}$) was introduced to each wheel (see Figure 4.). In the F_i coordinate systems the normal axis is parallel with the wheel's shaft (noted as n_i), the binormal direction is parallel with vertical direction (noted as b_i), and the tangential direction (noted as t_i) is perpendicular to both of the above directions. The lower index i represents the index of each driving block (i.e. M1, M2, M3).

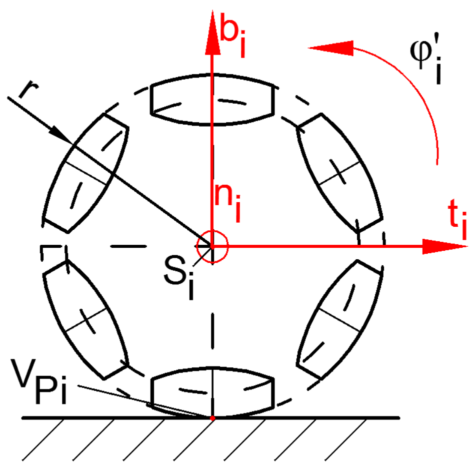

Figure 4. Side view of an idealized omni-wheel. Showing the wheel attached coordinate system $\mathcal{F}_i\{n_i, t_i, b_i\}$.

Using the notation of Figure 4 the wheel's angular velocities can be expressed as:

$$\overrightarrow{\varphi_1'}(t) = \begin{bmatrix} \varphi'_{n1}(t) \\ 0 \\ 0 \end{bmatrix}_{n_1 t_1 b_1} \quad (1)$$

$$\overrightarrow{\phi_2'}(\mathrm{t}) = \begin{bmatrix}\phi'_{n2}(t)\\ 0\\ 0\end{bmatrix}_{n_2t_2b_2} \qquad (2)$$

$$\overrightarrow{\phi_3'}(\mathrm{t}) = \begin{bmatrix}\phi'_{n3}(t)\\ 0\\ 0\end{bmatrix}_{n_3t_3b_3} \qquad (3)$$

Where $\phi'_{ni}(t)$ denotes the each wheel's angular velocity in the normal direction in its own coordinate system produced by their corresponding motors.

For the contact point velocity assuming no sliding in all directions:

$$\vec{V}_{pi} = \vec{0} \qquad (4)$$

Using the velocity transformation in one rigid body the translational velocities of the wheels' center point can be expressed as:

$$\overrightarrow{S_i'}(\mathrm{t}) = \vec{V}_{pi} + \overrightarrow{\phi_i'}(\mathrm{t}) \times \overrightarrow{r_w} + \begin{bmatrix}n_i'(t)\\ 0\\ 0\end{bmatrix} \qquad (5)$$

Where r is the radius of the wheels:

$$\overrightarrow{r_w} = \begin{bmatrix}0\\ 0\\ r\end{bmatrix}_{n_it_ib_i} \qquad (6)$$

And $n_1'(t)$ is an unknown velocity produced by the other two wheel looking from one wheel's point of view. $n_i'(t)$ can be imagined as a resultant velocity in case the robot is moving in one direction.

Applying (5) to each wheel the wheels' center of mass velocities have the following form:

$$\overrightarrow{S_1'}(\mathrm{t}) = \begin{bmatrix}n_1'(t)\\ -r\,\phi'_{n1}(t)\\ 0\end{bmatrix}_{n_1t_1b_1} \qquad (7)$$

$$\overrightarrow{S_2'}(\mathrm{t}) = \begin{bmatrix}n_2'(t)\\ -r\,\phi'_{n2}(t)\\ 0\end{bmatrix}_{n_2t_2b_2} \qquad (8)$$

$$\overrightarrow{S_3'}(\mathrm{t}) = \begin{bmatrix}n_3'(t)\\ -r\,\phi'_{n3}(t)\\ 0\end{bmatrix}_{n_3t_3b_3} \qquad (9)$$

Next based on Figure 3 a robot attached coordinate system was considered $\boldsymbol{\mathcal{F}_4\{\xi,\eta,\zeta\}}$, and another coordinate system what is fixed in space $\boldsymbol{\mathcal{F}_5\{x,y,z\}}$). The goal is to develop the above mentioned relationship in $\boldsymbol{\mathcal{F}_5}$, because $\boldsymbol{\mathcal{F}_5}$ is a reference frame not just a coordinate system. (see Figure 5).

On Figure 5 the wheels attached coordinate systems are also showed. The black rectangles on Figure 5 are representing the driving blocks.

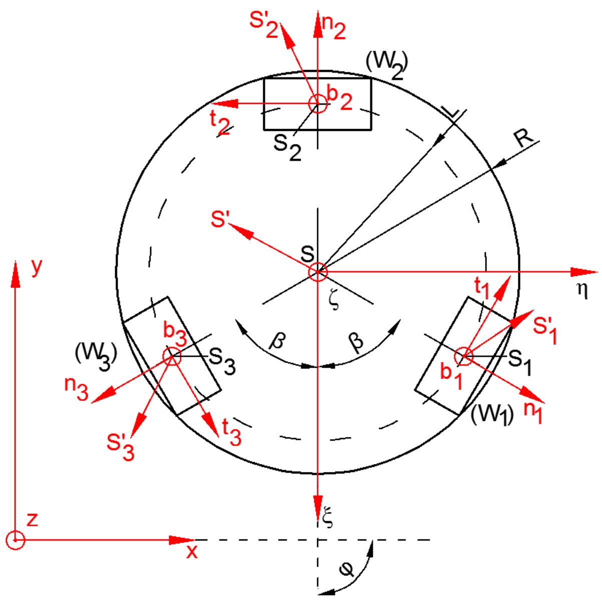

Figure 5. Top view of the idealized Omni-drive system. Showing the coordinate systems attached to the wheels ($\mathcal{F}_1$, $\mathcal{F}_2$, $\mathcal{F}_3$), the robot coordinate system ($\mathcal{F}_4$) and the global coordinate system ($\mathcal{F}_5$).

Using the notation of Figure 5 transformation matrices can be considered to transform vectors between from one coordinate system to another. Essentially the transformation between ($\boldsymbol{\mathcal{F}_1}$, $\boldsymbol{\mathcal{F}_2}$,$\boldsymbol{\mathcal{F}_3}$) and $\mathcal{F}_4$ is produced:

$$R_1 = \begin{bmatrix}\cos\beta & -\sin\beta & 0\\ \sin\beta & \cos\beta & 0\\ 0 & 0 & 1\end{bmatrix} \qquad (10)$$

$$R_2 = \begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & 1\end{bmatrix} \qquad (11)$$

$$R_3 = \begin{bmatrix}\cos\beta & \sin\beta & 0\\ -\sin\beta & \cos\beta & 0\\ 0 & 0 & 1\end{bmatrix} \qquad (12)$$

Where R_i is a simple rotation matrix about the b_i axis of each wheel's coordinate system, by a constant β angle. β is the half angle between every two wheels shaft.

Finally the transformation between $\mathcal{F}_4$ and $\mathcal{F}_5$ was considered:

$$R_G = \begin{bmatrix}\cos\phi_z(t) & -\sin\phi_z(t) & 0\\ \sin\phi_z(t) & \cos\phi_z(t) & 0\\ 0 & 0 & 1\end{bmatrix} \qquad (13)$$

Where $\phi_z(t)$ is the angle between ξ and x of the robot attached coordinate system and the reference frame. Here is noted that ζ and z are parallel.

In order to get the desired relationship between the coordinate velocities of the robot and the angular velocities of the wheels the following equations have to be solved:

$$\overrightarrow{S_1'}(\mathrm{t}) = \vec{S}(t) + \vec{\phi}'(\mathrm{t}) \times \overrightarrow{r_{SS1}} \qquad (14)$$

$$\overrightarrow{S_2'}(\mathrm{t}) = \vec{S}(t) + \vec{\phi}'(\mathrm{t}) \times \overrightarrow{r_{SS2}} \qquad (15)$$

$$\overrightarrow{S_3'}(\mathrm{t}) = \vec{S}(t) + \vec{\phi}'(\mathrm{t}) \times \overrightarrow{r_{SS3}} \qquad (15)$$

Where $\overrightarrow{S_i'}$ are the velocities of the wheels described in the $\mathcal{F}_5$ reference frame, $\vec{S}$ is the velocity of robot and:

$$\vec{S'}(t) = \begin{bmatrix} x'(t) \\ y'(t) \\ 0 \end{bmatrix} \tag{16}$$

$\vec{\phi}'(t)$ is the angular velocity of robot:

$$\vec{\phi}'(t) = \begin{bmatrix} 0 \\ 0 \\ \phi_z'(t) \end{bmatrix} + R_G\left(R_1\overrightarrow{\phi_1'}(t) + R_2\overrightarrow{\phi_2'}(t) + R_3\overrightarrow{\phi_3'}(t)\right) \tag{17}$$

And $\overrightarrow{r_{SSi}}$ are the vectors pointing from the robot's center of mass to each wheel:

$$\overrightarrow{r_{SS1}} = R_G \begin{bmatrix} L\cos\beta \\ L\sin\beta \\ 0 \end{bmatrix}_{\xi\eta\zeta} \tag{18}$$

$$\overrightarrow{r_{SS2}} = R_G \begin{bmatrix} -L \\ 0 \\ 0 \end{bmatrix}_{\xi\eta\zeta} \tag{19}$$

$$\overrightarrow{r_{SS3}} = R_G \begin{bmatrix} L\cos\beta \\ -L\sin\beta \\ 0 \end{bmatrix}_{\xi\eta\zeta} \tag{20}$$

L is the radius of the wheels' pitch circle.
Combining (14) to (20) yields:

$$R_G R_i \overrightarrow{S_i'}(t) = \vec{S}(t) + \vec{\phi}'(t) \times \overrightarrow{r_{SSi}} \tag{21}$$

Rearranging (21) to zero:

$$\vec{0} = \vec{S'}(t) + \vec{\phi}'^{(t)} \times \overrightarrow{r_{SSi}} - R_G R_i \overrightarrow{S_i'}(t) \tag{22}$$

Expounding (22) 3 vector equations can be obtained, what can be considered as 6 equations:

$$\vec{0} = \begin{bmatrix} -\cos(\beta + \phi_z(t))\, n_1'(t) + x'(t) + \sin(\beta + \phi_z(t))\,(r\,\phi_{n1}'(t) - L\,\phi_z'(t)) \\ -\sin(\beta + \phi_z(t))\, n_1'(t) + y'(t) + \cos(\beta + \phi_z(t))\,(L\,\phi_z'(t) - r\,\phi_{n1}'(t)) \\ 0 \end{bmatrix} \tag{23}$$

$$\vec{0} = \begin{bmatrix} \cos(\phi_z(t))\, n_2'(t) + x'(t) + \sin(\phi_z(t))\,(L\,\phi_z'(t) - r\,\phi_{n2}'(t)) \\ \sin(\phi_z(t))\, n_2'(t) + y'(t) + \cos(\phi_z(t))\,(r\,\phi_{n2}'(t) - L\,\phi_z'(t)) \\ 0 \end{bmatrix} \tag{24}$$

$$\vec{0} = \begin{bmatrix} -\cos(\beta - \phi_z(t))\, n_3'(t) + x'(t) + \sin(\beta - \phi_z(t))(L\,\phi_z'(t) - r\,\phi_{n3}'(t)) \\ \sin(\beta - \phi_z(t))\, n_3'(t) + y'(t) + \cos(\beta - \phi_z(t))(L\,\phi_z'(t) - r\,\phi_{n3}'(t)) \\ 0 \end{bmatrix} \tag{25}$$

Solving equations (23)-(25) for $x'(t), y'(t),\ \phi_z'(t),\ n_1'(t), n_2'(t), n_3'(t)$ yields:

$$\begin{bmatrix} \boldsymbol{x'(t)} \\ \boldsymbol{y'(t)} \\ \boldsymbol{\phi_z'(t)} \\ \boldsymbol{n_1'(t)} \\ \boldsymbol{n_2'(t)} \\ \boldsymbol{n_3'(t)} \end{bmatrix} = \\ = \begin{bmatrix} \frac{1}{4} r\, sec\left(\frac{\beta}{2}\right)\left(csc\left(\frac{\beta}{2}\right) cos(\phi_z(t))\,(\phi_{n3}'(t) - \phi_{n1}'(t)) - sec\left(\frac{\beta}{2}\right) sin(\phi_z(t))\,(\phi_{n3}'(t) - 2\,\phi_{n2}'(t) + \phi_{n3}'(t))\right) \\ r sin\left(\frac{\beta}{2}\right) csc^2(\beta)\left(\phi_{n1}'(t)\, sin\left(\frac{\beta}{2} - \phi_z(t)\right) - 2\, sin\left(\frac{\beta}{2}\right)\phi_{n2}'(t)\, cos(\phi_z(t)) + \phi_{n3}'(t)\, sin\left(\frac{\beta}{2} + \phi_z(t)\right)\right) \\ \frac{r\left(2\, cos(\beta)\,\phi_{n2}'(t) + \phi_{n1}'(t) + \phi_{n3}'(t)\right)}{2L\,(cos(\beta) + 1)} \\ \frac{1}{2} r\left((csc(\beta) - 2\, cot(\beta))\phi_{n1}'(t) - 2 tan\left(\frac{\beta}{2}\right)\phi_{n2}'(t) + csc(\beta)\,\phi_{n3}'(t)\right) \\ \frac{1}{2} r\, csc(\beta)(\phi_{n1}'(t) - \phi_{n3}'(t)) \\ -\frac{1}{2} r\, csc(\beta)\,(2(cos(\beta) - 1)\phi_{n2}'(t) + (1 - 2\, cos(\beta))\phi_{n3}'(t) + \phi_{n1}'(t)) \end{bmatrix} \tag{26}$$

(26) can be rearranged to the following form:

$$\begin{bmatrix} x'(t) \\ y'(t) \\ \phi_z'(t) \end{bmatrix} = T_{robot} \begin{bmatrix} \phi_{n1}'(t) \\ \phi_{n2}'(t) \\ \phi_{n3}'(t) \end{bmatrix} \tag{27}$$

Where T_{robot} is the pursued relationship between the wheel angular velocities and the robot's velocities:

$$T_{robot} \\ = \begin{bmatrix} -\frac{1}{4} r\, sec\left(\frac{\beta}{2}\right)\left(cos(\phi_z(t))\, csc\left(\frac{\beta}{2}\right) + sec\left(\frac{\beta}{2}\right) sin(\phi_z(t))\right) & \frac{r\, sin(\phi_z(t))}{cos(\beta) + 1} & -\frac{1}{4} r sec\left(\frac{\beta}{2}\right)\left(sec\left(\frac{\beta}{2}\right) sin(\phi_z(t)) - cos(\phi_z(t)) csc\left(\frac{\beta}{2}\right)\right) \\ r\, csc^2(\beta)\ sin\left(\frac{\beta}{2}\right) sin\left(\frac{\beta}{2} - \phi_z(t)\right) & -\frac{r\, cos(\phi_z(t))}{cos(\beta) + 1} & r\, csc^2(\beta) sin\left(\frac{\beta}{2}\right) sin\left(\frac{\beta}{2} + \phi_z(t)\right) \\ \frac{r}{2cos(\beta)L + 2L} & \frac{r\, cos(\beta)}{cos(\beta)L + L} & \frac{r}{2cos(\beta)L + 2L} \end{bmatrix} \tag{28}$$

2.2. Dynamics of the omni-directional drive[8][9]

In this section the relationship between the wheel torques and the robot's coordinate accelerations is pursued. In order to do this first consider general coordinates and general coordinate velocities:

$$\vec{q}(t) = \begin{bmatrix} x(t) \\ y(t) \\ \phi_z(t) \end{bmatrix}; \ \vec{q}'(t) = \begin{bmatrix} x'(t) \\ y'(t) \\ \phi_z'(t) \end{bmatrix} \qquad (29); (30)$$

The Lagrangian approach to deriving the equations of motion is based on the definition of a Lagrangian:

$$\mathcal{L}(\vec{q}(t), \vec{q}'(t)) = K.E._{Total}(\vec{q}(t), \vec{q}'(t)) - P.E.(\vec{q}(t), \vec{q}'(t)) \qquad (31)$$

$K.E._{Total}(\vec{q}(t), \vec{q}'(t))$ is the total kinetic energy of the dynamic system and $P.E.(\vec{q}(t), \vec{q}'(t))$ is its potential energy. The variable $\vec{q}(t)$ denotes the configuration of the system, which is the set of variables that can uniquely describe the position of the system at a fixed time. For an unconstrained system, Lagrange's equations of motion are derived from the Lagrangian as follows:

$$\frac{d}{dt}\left[\frac{\partial\mathcal{L}(\vec{q}(t), \vec{q}'(t))}{\partial\vec{q}'(t)}\right] - \frac{\partial\mathcal{L}(\vec{q}(t), \vec{q}'(t))}{\partial\vec{q}(t)} = \vec{T} \qquad (32)$$

Where $\vec{T}$ are the generalized forces acting on the system.

The case where the robot rolls around on a flat floor is considered (i.e., the case where the robot is climbing up on a ramp is ignored). In this case, the gravitational potential energy is constant, and so the Lagrangian is comprised solely of kinetic energy terms:

$$\mathcal{L}(\vec{q}(t), \vec{q}'(t)) = K.E._{Total}(\vec{q}(t), \vec{q}'(t)) \qquad (33)$$

Although the Robotino® is made up of 4 rigid body; 3 driving blocks and a main body only the kinetic energy of the main body is considered in this paper. This is due because the main body represents much bigger mass and inertia comparing to the sum of driving blocks. The kinetic energy of the main body is:

$$K.E._{body}(\vec{q}(t), \vec{q}'(t)) = \frac{1}{2} m_{robot} \left\|\vec{S}'(t)\right\|^2 + \frac{1}{2}\vec{\Phi}'(t)^T \theta_{body} \vec{\Phi}'(t) \qquad (34)$$

Where θ_{body} is the main body's inertia in the reference frame and:

$$\theta_{body} = \begin{bmatrix} \frac{m_{robot}(3R^2 + h^2)}{12} & 0 & 0 \\ 0 & \frac{m_{robot}(3R^2 + h^2)}{12} & 0 \\ 0 & 0 & \frac{m_{robot} R^2}{2} \end{bmatrix}_{xyz} \qquad (35)$$

Combining (31), (34) and (35) yields:

$$K.E._{Total}(\vec{q}(t), \vec{q}'(t)) = \frac{1}{4} m_{robot}(R^2 \phi_z'(t)^2 + 2x'(t)^2 + 2y'(t)^2) \qquad (36)$$

And the Lagrange's equations of motion are taking the form:

$$\begin{bmatrix} m_{robot} & 0 & 0 \\ 0 & m_{robot} & 0 \\ 0 & 0 & \frac{m_{robot} R^2}{2} \end{bmatrix} \begin{bmatrix} x''(t) \\ y''(t) \\ \phi_z''(t) \end{bmatrix} = \vec{T} \qquad (37)$$

And for $\vec{T}$:

$$\vec{T} = T_{robot} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \qquad (38)$$

Where τ_1, τ_2, τ_3 are the wheel torques.

Reorder (37) and using (38) the desired relationship is obtained:

$$\vec{q}''(t) = \begin{bmatrix} m_{robot} & 0 & 0 \\ 0 & m_{robot} & 0 \\ 0 & 0 & \frac{m_{robot} R^2}{2} \end{bmatrix}^{-1} T_{robot} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \qquad (39)$$

2.3. The State Space model[11]

Considering the general form of the State Space model of a linear time-invariant system:

$$\begin{aligned} \dot{x}(t) &= A\,x(t) + B\,u(t) \\ y(t) &= C\,x(t) + D\,u(t) \end{aligned} \qquad (40)$$

Where $x(t)$ is a vector of the time dependent state variables, $\dot{x}(t)$ is the first derivative of $x(t)$. $u(t)$ is a vector of system inputs. $y(t)$ is a vector of the system output variables. A, B, C, D are constant matrices representing the system equations.

Equations (27) and (39) can be used to formulate the State Space model of the Omni-drive system. For $x(t)$ and $u(t)$ the following has been chosen:

$$\boldsymbol{x}(\boldsymbol{t}) = \begin{bmatrix} \vec{\boldsymbol{q}}(\boldsymbol{t}) \\ \vec{\boldsymbol{q}}(\boldsymbol{t}) \end{bmatrix}, \quad (41),$$

$$\boldsymbol{u}(\boldsymbol{t})^{T} = [\boldsymbol{\phi}'_{n1}(\boldsymbol{t}) \quad \boldsymbol{\phi}'_{n2}(\boldsymbol{t}) \quad \boldsymbol{\phi}'_{n3}(\boldsymbol{t})\ \boldsymbol{\tau}_1 \quad \boldsymbol{\tau}_2 \quad \boldsymbol{\tau}_3] \quad (42)$$

For the $\boldsymbol{A}$ system matrix the following can be written:

$$\boldsymbol{A} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (43),$$

$$\boldsymbol{B} = \begin{bmatrix} \boldsymbol{T}_{robot} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{M}^{1}\boldsymbol{T}_{robot} \end{bmatrix} \quad (44)$$

3. Conclusions

In this paper a State Space model was given to the Omni-directional drive train based on the mechanical construction. The model is enabling students and researchers to work with in the education and other fields of interest. Although the given model is in preliminary stage and many assumptions were made, it is satisfactory in many aspects. Our future plan is to further improve the model. Also numerical simulation and finally implementation in the chosen robot the Robotino®.

4. Acknowledgements

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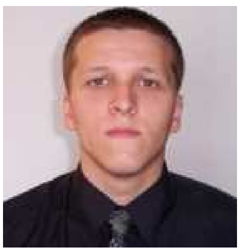

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