Omnidirectional Wheel Simulation – a Practical Approach

Viktor Kálmán

Budapest University of Technology and Economics,
Department of Control Engineering and Information Technology,
Magyar Tudósok körútja 2., Budapest 1117
Phone: 1 463 4025, fax: 1 463 2204
e-mail: kalman@iit.bme.hu

Abstract: In this paper a configurable omnidirectional wheel model is presented, which can be used for dynamic simulation and parameter tuning of omnidirectional robotic systems. First a brief overview is given on well known omnidirectional wheel designs and models from the literature, then two modeling approaches are described and compared. The usability of the models is verified by simulation, using two omnidirectional platforms and kinematic equations from the literature. This work has been carried out using the Dymola modeling environment and the Modelica language.

Keywords: omnidirectional wheel, simulation, Modelica, mobile robotics

1. Introduction

Omnidirectional wheels have been invented quite a long time ago [8] and they have a rich history in the literature. They have been used for various tasks and many different embodiments are known [17], [4]. They are constructed so that a vehicle equipped with them can execute true holonomic movements, in other words it can change its direction of movement without changing its orientation. Their great movement capabilities however mean that their mechanical construction is complicated, they also require independent drive and control systems for each wheel. The rolling efficiency of these wheels is worse than that of regular wheels, also they generally do not perform very well on rough surfaces, i.e. they are best suited for indoors applications. Their use ranges from robotic soccer applications, through industrial heavy load transporters [19], and vehicle simulators [1], to educational and entertainment projects like the popular inverted pendulum, but mounted on a ball [12], [2]. Figure 1. shows some of these applications.

1.1. Motivation

To be able to use robotic systems on a professional level, simulation of the individual components and the system as a whole is necessary in the design phase. Modern engineering uses simulation for almost every task imaginable, to cut costs, speed up development and minimize changes late in the product life cycle. Omnidirectional platforms are no exception since they require more complex mechanical design and control, than traditional vehicles.

Figure 1: Examples for the use of omnidirectional wheels[1]

Probably the most important part of a vehicle model is the wheel, since this is the part that makes contact with the ground and transfers forces and torques to move the vehicle. In the last few decades a great number of wheel models of different levels of complexity have been constructed, and are used regularly in automotive and heavy truck simulations. This wealth of knowledge on wheel modeling however has not been applied extensively to other areas of vehicle simulation, such as mobile robotics, although there are a lot of common features between the two.

1.2. Simulation tool - Modelica

Modelica is a free object-oriented modeling language, with a textual definition to describe physical systems in a convenient way, by differential, algebraic and discrete equations. It is supported by the Modelica Association[2]. “It is suited for multi-domain modeling, for example, mechatronic models in robotics, automotive and aerospace applications involving mechanical, electrical, hydraulic and control subsystems, process oriented applications and generation, and distribution of electric power. Modelica is designed such that it can be utilized in a similar way as an engineer builds a real system: First trying to find standard components like motors, pumps and valves from manufacturers' catalogues with appropriate specifications and interfaces and only if there does not exist a particular subsystem, a component model would be newly constructed based on standardized interfaces.

Models in Modelica are mathematically described by differential, algebraic and discrete equations. No particular variable needs to be solved for manually. A Modelica

---

[1] [12], www.airtrax.com, www.kuka-omnimove.com, [1], [20]

[2] https://modelica.org (Accessed 2012. Feb.).

tool will have enough information to decide that automatically. Modelica is designed such that available, specialized algorithms can be utilized to enable efficient handling of large models having more than hundred thousand equations. Modelica is suited (and used) for hardware-in-the-loop simulations and for embedded control systems." [15] From my point of view the main attractiveness lies in the languages' object oriented nature, which allows a convenient incremental development workflow. Another attractive feature is the model building philosophy of describing the systems by algebraic differential equations, thus approaching the problem from a physics point of view, as opposed to a mathematical one, which – in my experience – is less appealing to an engineer.

1.3. Outline

A configurable omnidirectional wheel model was created that can be adapted to work with most of the popular empirical wheel models used in vehicle simulation today. With the help of this simulation configurable omnidirectional platform models were created and experiments were conducted with the most widely used configurations, the four wheeled Mecanum platform and the three wheeled omnidirectional platform, sometimes referred to as the kiwi drive platform.

The omnidirectional wheel model described in the first part of the article uses a tire model which is available in the Modelica Vehicle Dynamics Library that is included in the academic bundle-version of Dymola 7.4. This model is based on the well-known Rill tire model and handles collision, generates tire forces and torques. My wheel model extends this tire model and creates a roller model which is the basic element of an omnidirectional wheel using two different modeling approaches. In the second part of the paper some simulation results with a four wheeled industrial forklift model and a three wheeled platform are presented. The last part of the paper evaluates the results, gives usage hints and points out future improvement possibilities.

The work was carried out in the Fraunhofer IFF Magdeburg in cooperation with BUTE.

2. Wheel modeling

In this section a short overview is given on the most popular types of omnidirectional wheels and the basic ideas used for modeling them. Later the main concepts of empirical modeling of car tires are highlighted.

2.1. Omnidirectional wheel models

A great number of omnidirectional wheel users fall into the category of industrial companies and users of their product, the most significant being KUKA Robotics[3], and Airtrax[4]. The second group of people who use them fall into the category of students, preparing for robotics competitions such as RoboCup and others, or scientists working on advanced mobility concepts. This second group creates the majority of publications.

---

[3] http://youbot-store.com/, http://www.kuka-omnimove.com

[4] http://airtrax.com

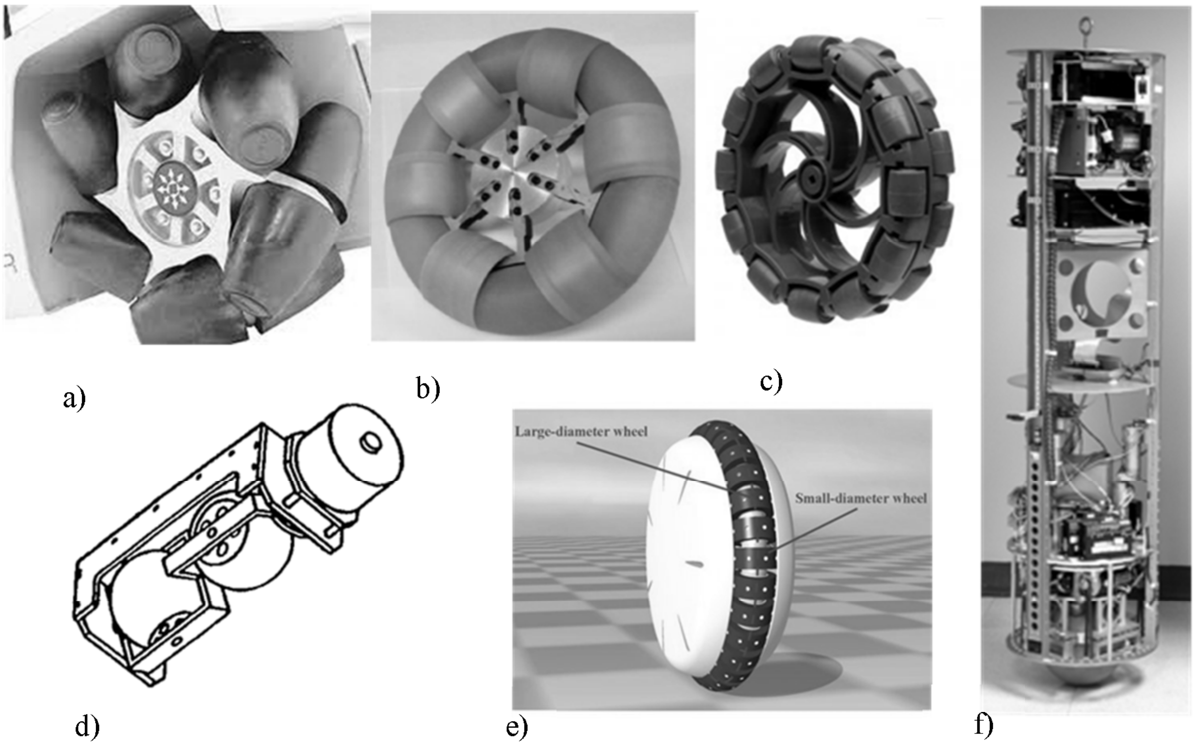


Figure 2 Different omnidirectional wheels and mobility concepts

a) Airtrax Mecanum wheel b) enhanced profile omni-wheel [5] c) multiple row wheel[5] *d) Killough wheel*[6] *e) wheel of a Honda U3-X personal mobility platform f) Ballbot, omnidirectional balancing robot [13]*

Figure 2. shows a cross section of some of the wheel designs and interesting mobility concepts. They were collected to demonstrate relevant concepts trough examples. Subfigures a), b) and c) represent the most popular wheel configurations i.e. passive rollers on the perimeter of a wheel. a) shows the Mecanum wheel used on the Airtrax forklift. It is worth noting that the rollers are shaped in an attempt to attain a round profile and have only a single roller touching the ground at a time. One of the problems associated with omni-wheels is the rough ride associated with changes in wheel radius when changing roller contact. Another important effect is caused by the rigid discontinuities between rollers, they cause slip especially on soft surfaces, such as a carpet [23]. b) and c) are examples of the most widely used solutions to these problems. b) uses different sized rollers, where the larger diameter rollers are shaped so that they can fit the smaller rollers inside, thus virtually eliminating the non-rolling surface on the circumference [5]. This obviously comes at the price of increased complexity. c) is a more common solution, by using multiple regular wheels mounted side by side at an angle, so that “bumpiness” and roller discontinuities can be minimized.

The remaining three subfigures show somewhat different mobility concepts. d) shows the so-called Killough wheel, named after the inventor [17]. In this concept two quasi ball-shaped rollers are mounted in rigid brackets that are connected perpendicular to

---

[5] http://www.vexrobotics.com

[6] http://www.h33.dk/opfhjul_index.en.html

each other. The rollers are free to roll and the bracket assembly is driven by a motor. These wheels should be mounted and applied just like the omni-wheels above. (More on Kinematic constraints can be read in [9]) Smooth ride and single roller contact is ensured by the shape of the rollers, the contact point however moves significantly when roller contact changes.

Subfigure e) shows the wheel of Honda U3-X[7] personal mobility platform. A seat is mounted on top of the wheel and the vehicle balances and drives on this single wheel in an omnidirectional fashion. This is achieved by powered rollers in addition to the main drive that turns the entire wheel.

f) shows an omnidirectional platform that clearly eliminates any rolling imperfections by using a ball to ride on. It is called Ballbot and it was designed to work in areas used by people [13]. It is high enough to make eye contact yet it has a small footprint, that together with omnidirectional maneuverability enables it to get around in cluttered indoor environments.

My model can be used to describe the type of wheels represented by the first three subfigures. A common characteristic is that they have a relatively small width relative to their diameter and they are designed with an attempt to ensure smooth ride. In the following let us take a look at how this type of wheels has been modeled by other researchers.

Williams et al. [23] developed a wheel model motivated by the RoboCup competition. They used a small three wheeled platform with 0° rollers (Figure 3. a). The wheels they used had a single row of rollers, without any provisions to smoothen roller discontinuities, this was reflected in their results, the wheels demonstrated a strong angle dependent friction characteristics directly related to the non-rolling part touching the carpet they used for testing. It is also important to note that they found that the friction coefficient in the driven and in the free rolling direction was comparable – 3/1 and 5/3 respectively for paper and carpet – showing that the quality of the omni-wheel greatly effects the behavior of the mobile platform.

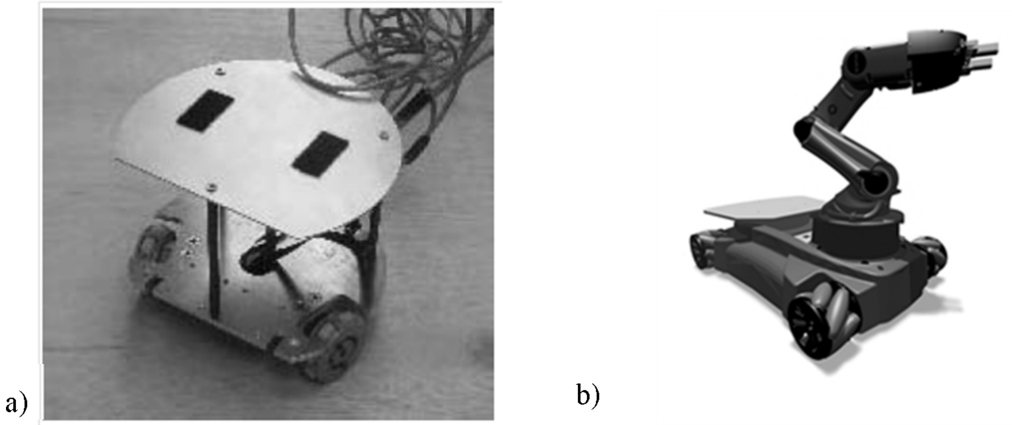

a) b)

Figure 3 a) Omnidirectional RoboCup player by Williams et al. [23], b) youBot by KUKA Robotics, flexible arm on a mobile base

---

[7] http://www.hondanews.com

Dresscher et al. [6] developed a modular model for youBot (Figure 3. b) using an energy based method and its bond graph representation. Their goal was to model this rather complicated platform in a modular, reusable fashion, this also includes modeling the Mecanum wheels. To make the model simpler they neglected the dynamic behavior of the wheels and derived a kinematical model from the geometry. They neglected friction in the roller bearings and generally neglected force in the free rolling direction. They defined a transformation between drive axis movement and wheel movement in the direction parallel to the roller axis. Floor contact was modeled with a resistance and a stiffness parameter. The authors had no opportunity to validate their model on the real platform.

Tobolár et al. [21] created an object oriented library for Mecanum wheels in Modelica, unfortunately their article is very short and non-informative. As the author explained this is due to an NDA with KUKA Robotics.

Studying the literature the conclusion can be drawn, that in many cases omnidirectional platforms are modeled as a whole, assuming symmetrical load distribution, without having separate wheel models. However when wheels are modeled, dynamic effects are often neglected and the results are purely kinematical. This is probably justified when the platform has very low, known weight, for example a RoboCup player. Another common modeling approach is that wheel forces are assumed to be generated parallel to the direction of the rollers and forces perpendicular to the roller axis are assumed to be zero. An exception is the paper mentioned before [23], where the authors had to calculate with substantial forces in the free rolling direction, however in my opinion this was due to the disadvantageous characteristics of the omni-wheel they used.

To be able to apply a wheel model that accommodates a broad range of robotic platforms including heavy machines, with uneven load distribution and various wheel designs with different roller materials, a model is needed that is easy to parameterize, includes simple dynamics, handles sliding and last but not least of all, well suited for simulation. For this a choice was made to build on the well proven results from the domain of regular tire modeling, while applying some of the techniques used in the literature cited above.

2.2. Regular tire models in simulation

Tire modeling in general has been an active area of research for a long time, because the behavior of a tire is a complex phenomenon, and the results can be used in countless applications, making it both a challenging and lucrative area of research. The main purpose of a tire, besides providing a smooth ride for the passengers is to transmit forces and torques in three mutually perpendicular directions to create vehicle movement and directional control. To achieve this, a tire model has to handle collision, calculate the contact patch with the ground and obstacles, and it has to generate the forces and torques that arise. Most of these calculations are nonlinear because of the characteristics of the tire material [3].

Instead of creating a model from scratch, already existing models in Modelica were used as a basis, thus not having to recreate well proven components.

The simplest models regard the tire as a rigid disk, with unchangeable radius and linear dynamic properties, the most complicated ones use finite element simulation, fine tuned to a certain rubber compound and carcass. For a tire model to be useful, a compromise between complexity and accuracy has to be found depending on the application at hand. A very good example of incremental model building in Modelica is given by [24].

Except for simple targeted experiments the model cannot be restricted to a certain driving situation. Most of the relevant cases have to be considered, such as driving with nonzero camber and sideslip angles. Another important aspect is the adaptability of tire model characteristic parameters to real world tire behavior. Most experimental tire models such as the well-known Magic formula by H. Pacejka, or TMeasy by G. Rill [7], [16], [18] uses polynomial approximation of real measured data curves. These polynomials and the conditions of switching between them describe the tire characteristics, for given external parameters. An example according to the Rill model is given in Figure 4. The curve is valid for constant coefficient of friction μ and vertical load F_Z.

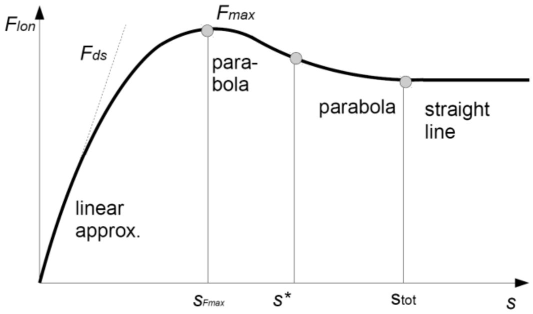


Figure 4: Steady state longitudinal force vs. wheel slip approximation according to [7] for a given μ and vertical load

Slip is usually defined in relation to the difference between a wheel center's velocity and its circumferential velocity. It is often confused with sliding, but it is important to see that slip occurs with a perfectly gripping tire as well. It can be thought of as the driven axis twisting the elastic tire material around itself.

2.2.1. The Rill tire model

A very appealing aspect of the Rill model is that its parametrization is intuitively simple, containing only a few parameters, with physical meaning, in contrast to for example the magic formula, which uses a lot of curve approximation parameters with no direct physical meaning. The parameter values matching measurement data are available from certain manufacturers for some of their products. Nevertheless one would need to match experimental data again when creating a new model for an unknown tire, thus restricting the usage of this kind of modeling to users well equipped with tools for tire identification.

The Rill model is a semi-empirical tire model with first order dynamics. Wheel parameters for steady state force generation are approximated quadratically from two load tables: one similar to Table 1 - for a nominal F_Z - and another one for $2F_Z$. Table 1 shows some typical values used in the Modelica libraries and [18], for reference. The indices x and y stand for longitudinal and lateral values, respectively.

Table 1: Load table for Rill model and typical values

Name	Description	Typ. value
F_{znom1}	Nominal normal force	3000N
F_{ds_x1}	Slope at $s_x = 0$	50000N
s_{max_x1}	Slip of maximum tire force	0.15
F_{max_x1}	Maximal tire force	3000N
s_{slide_x1}	Slip where sliding begins	0.4
F_{slide_x1}	Force where sliding begins	2800N
F_{ds_y1}	Slope at $s_y = 0$	40000N
s_{max_y1}	Slip of maximum tire force	0.21
F_{max_y1}	Maximal tire force	2750N
s_{slide_y1}	Slip where sliding begins	0.6
F_{slide_y1}	Force where sliding begins	2500N

The other load table contains values for $2F_{znom1} = F_{znom2}$ *and the quadratic interpolation for* $F_z < 2F_{znom1}$ *for any value is demonstrated trough the example of* F_{ds_x}:

$$F_{ds\_x} = \left[\left(\frac{F_{dsx_2}F_{znom1}}{F_{znom2}} - \frac{F_{dsx_1}F_{znom2}}{F_{znom1}}\right)\left(\frac{F_{znom1} - F_{znom}}{F_{znom1} - F_{znom2}}\right) + \frac{F_{dsx1}\,F_{znom}}{F_{znom1}}\right]\frac{F_{znom}}{F_{znom1}} \quad (3)$$

The interpolation curve for given parameter values is shown on Figure 5.

Besides the tire load parameters some dynamic parameters also have to be set. The model uses first order dynamics counting with a dynamic force according to the following - in direction x:

$$F_{dyn\_x} = c_x e_x + d_x \dot{e}_x \quad (2)$$

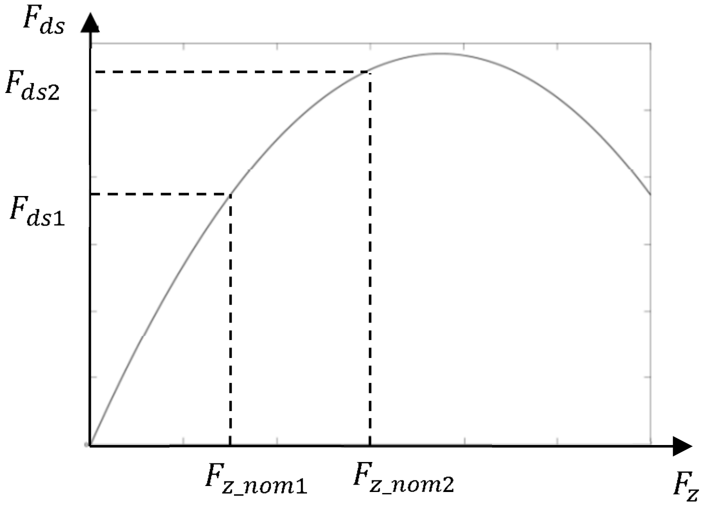


Figure 5: Force curve gradient quadratic interpolation example, F_{ds_x} *vs. vertical load*

Meaning of the parameters is explained in Figure 6 according to [18], where e_x is the longitudinal tire deformation and c_x and d_x are the lateral stiffness and damping, respectively. Typical values for c_x and d_x are 100000 N/m and 1500 Ns/m. In the z and y directions the behavior is similar, however the constants might differ.

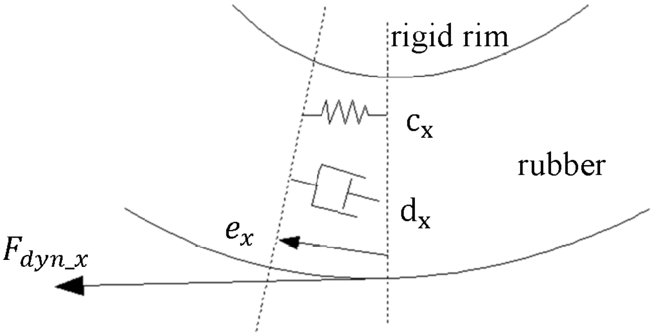


Figure 6: First order tire dynamics

2.3. Omnidirectional models based on regular tires

Two distinct approaches were used to adapt regular models to omnidirectional operation. These are documented in the following sections. Both models can be adapted to use various tire models – not just the Rill model – as a basis.

2.3.1. Using individual rollers

The most straightforward method to create a usable Mecanum wheel model:

- take any tire model from the library to create a roller from the base model
- set estimated (or measured) wheel parameters and geometry
- set a certain number of rollers and arrange them according to the given wheel geometry
- allow the rollers to spin freely along their main axis and connect them to a main axle, that can be driven by an appropriate angular velocity or torque

This is illustrated on Figure 7, with a Mecanum wheel, where "frame_a" is the fixed wheel hub, the wheel is driven by the "speed" variable (angular velocity) "rollerRot" creates the 45° rotation and "spoke" defines the position of each roller wheel around the perimeter. The number of rollers is configurable trough a user-defined parameter.

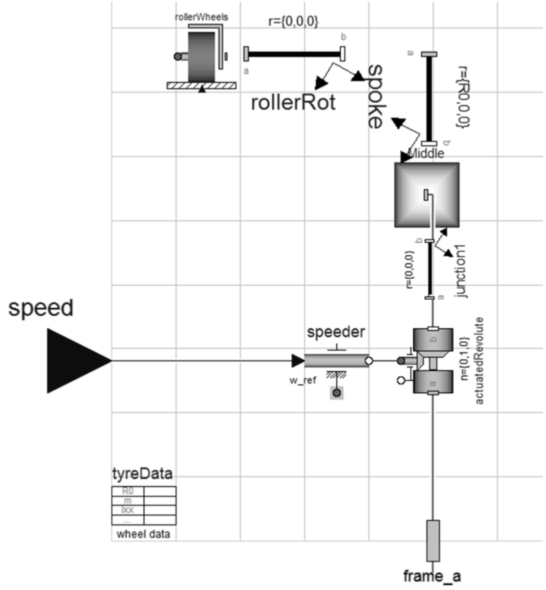
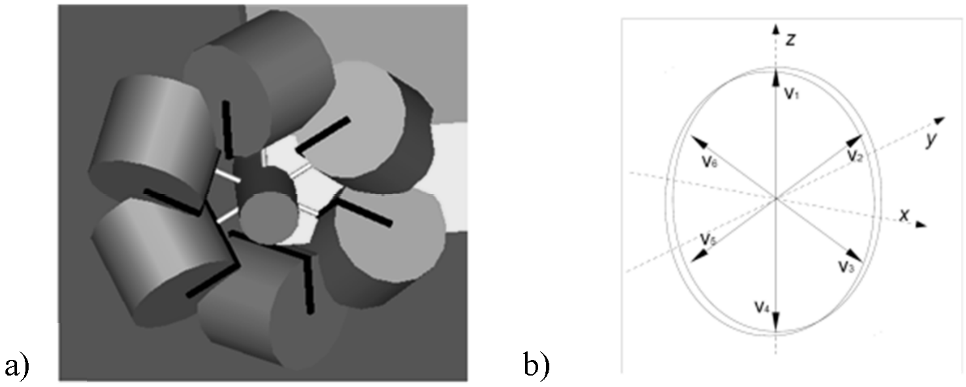


Figure 7: Mecanum wheel model of an individual roller in Modelica

An example animation result for six rollers can be seen on Figure 8 a). The spokes – basically the vectors pointing at rollers' centers – are computed according to Figure 8 b). Each wheel's local x-direction points forwards while the z-axis points upwards. Together with the y axis these create a right handed coordinate system.



a) b)

Figure 8: Animation a) and virtual spokes b) of a Mecanum wheel

As the wheel lies in the x-z plane, the spoke vectors – starting at the wheel's origin – are obtained the following way:

$$v_i = R_0 \left\{ \sin\frac{2\pi i}{n}, 0, \cos\frac{2\pi i}{n} \right\} \tag{3}$$

where i goes from 1 to n which is the number of rollers and R_0 is the spoke length.

This approach is straightforward, since it copies wheel mechanics, and it does work fairly well in simulation:

- Straightforward implementation.
- Very easy to switch between different tire models.
- Implicitly handles roller inertia, and rolling resistance.
- The model demonstrates "bumpiness" when it rolls from a roller to another, real mecanum wheels cause a bit of unevenness when rolling too.
- If simulation time is not an issue, adding more rollers and/or a better contact geometry model could make it more realistic.

It also suffers from several disadvantages.

- Far from suitable for real time simulation. Complicated model - for a typical four wheeled six roller vehicle, collision detection and force calculation has to be carried out for 24 rollers.
- Relies on boundaries of original wheel model. The individual rollers operate at extreme situations: up to 90° sideslip and camber angles. The tire model can handle this, but it was not designed for it.
- Crude contact model, most Mecanum wheel rollers are conical. In order to make them ride smoother, they have a varying cross section and rounded edges instead of being regular cylinders. A better geometry model would add complexity (see first point).

Naturally all these problems can be solved, however at a price of violating the principle of the original goal of creating a simple yet realistic wheel model, using available components. This approach would need a new contact model and a new roller design, from the start.

2.3.2. Single roller model

To overcome some of the disadvantages of the model presented above another one was created, based on a different approach. The main idea is to alter the force generation method of a single tire to behave like an omnidirectional wheel, applying some of the basic ideas summarized in section 2.1.

For a real Mecanum wheel the number of rollers touching the ground varies between one and two, creating an angle dependent effect on the wheel forces. However, in this model we assume that the force generation is continuous along the perimeter of the wheel much like an extrapolation of the ideal case when the center of only a single roller touches the ground. This is reasonable as the rollers are usually shaped in an attempt to achieve this effect. (see Figure 2)

To describe the modifications let us introduce the notation system used in the Rill model and the Modelica model for a regular wheel. They use the C (carrier) and W (wheel) coordinate systems according to the TYDEX [22] notations. "The C-axis system is fixed to the wheel carrier with the longitudinal xc-axis parallel to the road and in the wheel plane (xc-zc-plane). The origin of the C-axis system is the wheel center.

The origin of the W-axis system is the road contact-point defined by the intersection of the wheel plane, the plane through the wheel carrier, and the road tangent plane".[8]

The unit vectors Ce_x, Ce_y, Ce_z and We_x, We_y, We_z, point in the direction of the C and W system axes. To accommodate the omnidirectional wheel, we define a We_{fw} unit vector in the direction of the rollers' axis that is the direction it can exert force (see Figure 9)

$$We_{fw} = We_x \cdot Rot_\delta \tag{4}$$

where Rot_δ is a 3x3 rotation matrix of δ.

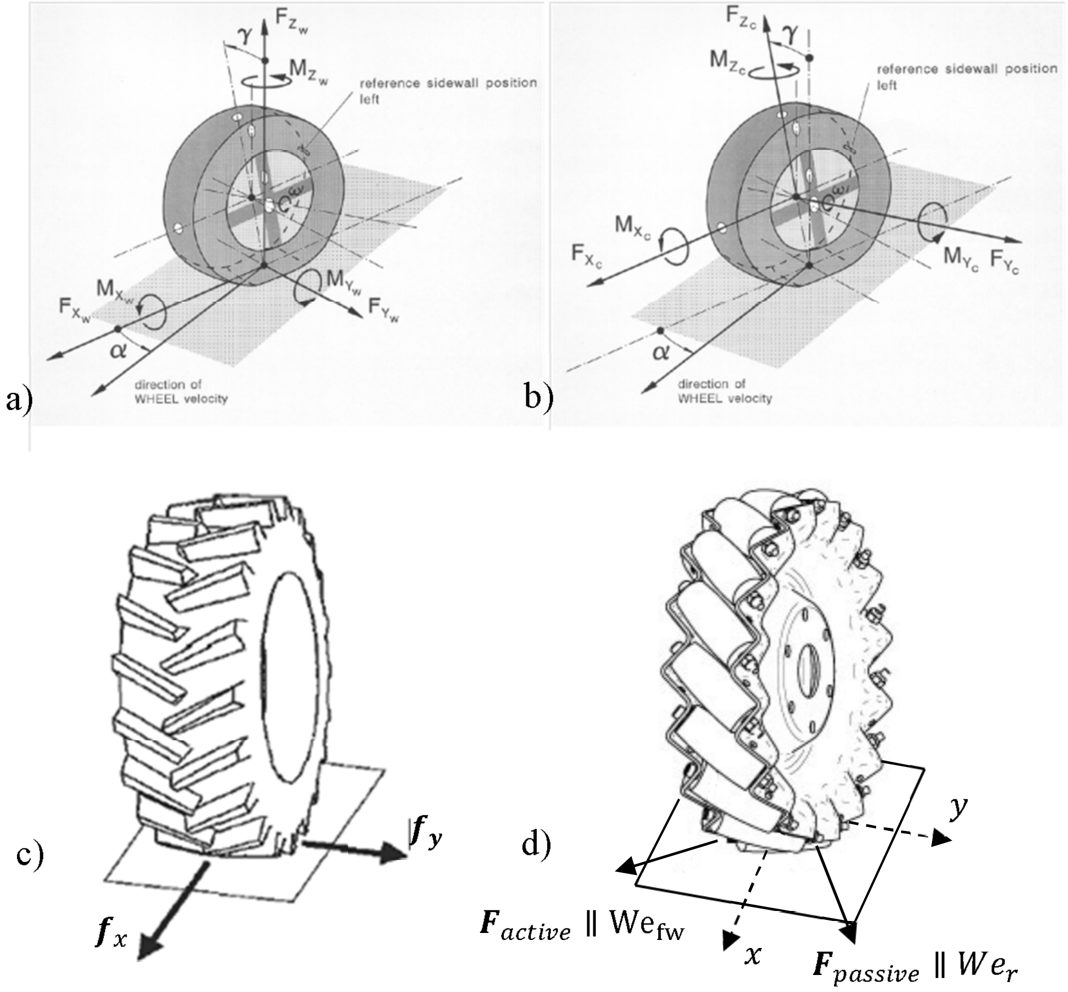


Figure 9: Definition of roller vectors a)Tydex C-axis system b) Tydex W-axis system c) Forces in the ground plane, regular wheel d) Forces in the ground plane omni-wheel

For the sake of simplicity we assume that the wheel does not exert any force to the direction of We_r - that is the free rolling direction perpendicular to We_{fw} . A more detailed model could include roller inertia and/or rolling resistance. Having made this assumption, we can make a further step by defining slip for the Mecanum wheel. In most wheel models forces are generated as a function of slip, so this is an important

---

[8] http://ti.mb.fh-osnabrueck.de/adamshelp/ (accessed May 2012)

aspect. Slip is defined separately for the x and y directions. Since our idealized roller only generates force in the direction of its spin axis (We_{fw}) we shall only calculate slip in this direction. [18] defines slip as "total slip":

$$s = \frac{v}{R|\Omega| + v_{num}} \quad \text{where} \quad v = \sqrt{v_x^2 + v_y^2} \tag{5}$$

R is the wheel radius, Ω is the angular velocity, and V_{num} is a small number inserted for numerical reasons. In our model we modify v in the slip equation:

$$v_{mecanum} = \sqrt{v_{fw}^2} \tag{6}$$

where v_{fw} is the projection of the velocity of the center of the wheel in the We_{fw} direction.

After redefining the slip equation, all we need to do is equate static and dynamic force equations with zero in the y direction and calculate force in the x direction according to the Rill model using the modified slip equation. The direction of this force has to be set to the direction of We_{fw}. At this point the effects of camber, rolling resistance and bore torque were not investigated.

3. Usage

The model described in this paper was used to simulate an industrial robotic transport vehicle, a forklift with a Mecanum wheel and a three wheeled robot with $\delta = 0^o$ omni-wheels. To use a Mecanum wheel, the most popular configuration is to put four of them on a platform in a way so that the rollers on the ground form a rhomboid, for the other platform a symmetric configuration is preferable Figure 10. (Other configurations, using more wheels and asymmetry are possible, for a general kinematics discussion see [9])

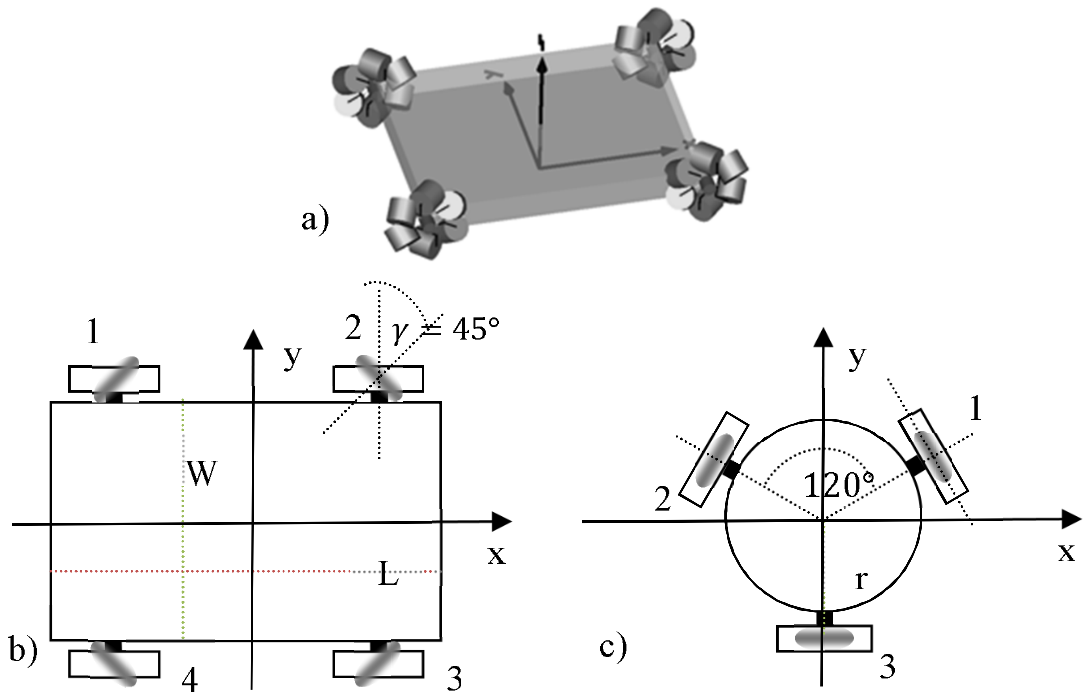


Figure 10 Illustration of wheel setup for two popular omnidirectional platforms

To obtain the correct wheel setup the front left and the rear right wheels have to be mirrored meaning that for them

$$\mathrm{We}_{\mathrm{fw}} = \mathrm{We}_{\mathrm{x}} \cdot \mathrm{Rot}_{-45^\circ} \tag{7}$$

Figure 10 a) depicts a model with the separate rollers model (section 2.3.1) for better visibility of wheel orientation, naturally the same configuration is used in the single-roller model (section 2.3.2) with - δ rotation. The virtual experiments were carried out on a flat surface, therefore to keep it as simple as possible, no suspension was simulated. The platform body was represented by a mass with inertia, and the load by a point mass.

Wheel parameters can be set intuitively or by making simple measurements. At the time of writing the author had no means to identify experimental parameters, so only intuitively set values were taken. Basically a stiff wheel with small carcass was used to model the lack of an inflated tire body.

The general kinematic equations for controlling the platform are well known from the literature [14], [9] Mecanum platform:

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

Where the ω-s designate angular velocities for each wheel numbered according to Figure 10, R is the wheel radius, L and W are length and width of the platform, v_x,v_y are platform velocities in local coordinates and Ω is the platform angular velocity.

Three wheel platform:

$$\begin{pmatrix}\omega_1\\ \omega_2\\ \omega_3\end{pmatrix}=\frac{1}{R}\begin{pmatrix}0.5 & -\frac{\sqrt{3}}{2} & -r\\ 0.5 & \frac{\sqrt{3}}{2} & -r\\ -1 & 0 & -r\end{pmatrix}\begin{pmatrix}v_{c_x}\\ v_{c_y}\\ \Omega\end{pmatrix} \tag{9}$$

By using these well known equations we were able to verify whether our wheels move the platform as expected.

Figure 11 a) shows an experiment with single-roller Mecanum wheels. The arrows at the wheels represent the driving force generated at the contact point.

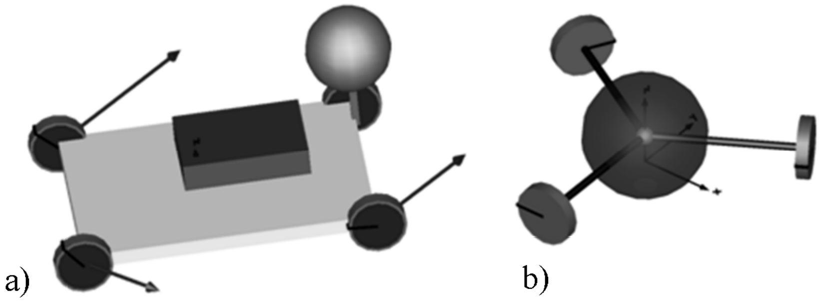


Figure 11 a) Forklift model with single roller Mecanum wheels b) Three wheeled platform with 0° omni-wheels

Figure 12 demonstrates the maneuverability of the platforms and the usability of the wheel model. Captured moments of a turn-while-translate movement can be seen (sampling not equidistant, for better visibility).

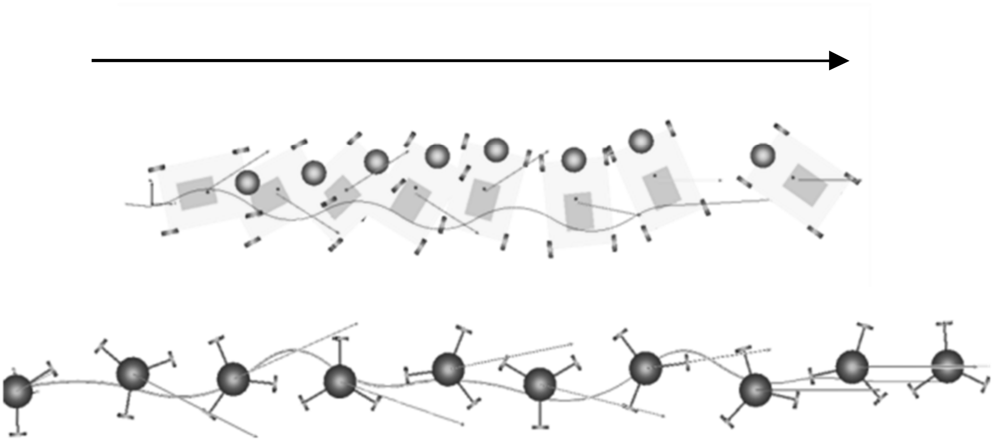


Figure 12 Turn-while-translate maneuver with zigzag movement

The platform continuously changes its orientation while translating in x and y directions simultaneously. The blue curve represents the trajectory of a chosen chassis point. The instantaneous speed vector is displayed as a green arrow.

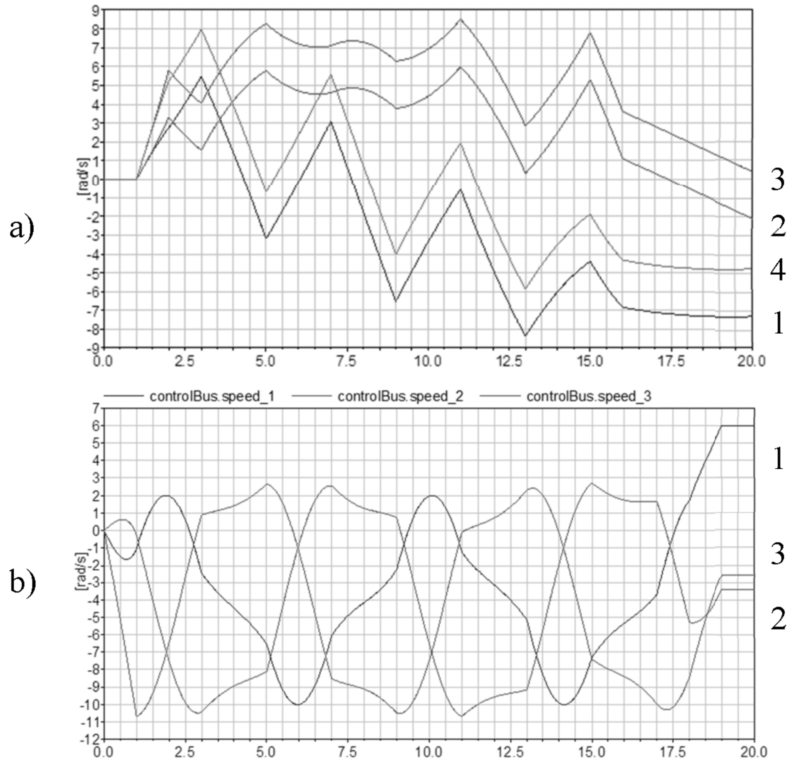


Figure 13 Angular velocity commands vs. time for a) Mecanum b) three wheel platforms while performing a turn-while-translate maneuver with zigzag

Figure 13 shows the angular velocity control signals versus time, exported from Dymola for each wheel. The angular velocities are constantly changing, to create the prescribed motion pattern.

These robot models can be used for trajectory generation and controller design tasks, as well as dynamic behavior tests for safety applications. A slip-based center of gravity estimation method is described in [11], and a brake assistant for omnidirectional wheels is published in [10]. For these works the single roller omnidirectional wheel model was used.

4. Scope - future prospects

The model follows the structure used by the Modelica library so integration into existing designs is simple. At this point the model has only been used for experiments on flat ground and zero camber angle. As real omnidirectional wheels are usually used under these conditions it is a reasonable simplification. However, modeling the effect of small obstacles and ground inclinations could be an interesting research topic. In my second – single roller – model the physical effects due to multiple individual rollers, were totally neglected. In order to make the wheel model more accurate, further dynamic effects such as roller inertia, rolling resistance could be incorporated. A possibly more important factor is the consideration of roller discontinuities. When two adjacent rollers come into contact with the ground, they might cause small fluctuations in effective wheel radius, contact location and also change the slip characteristics when multiple contact points occur. This effect could be incorporated by multiplying existing force characteristics with an angle dependent function, related to this effect. The omnidirectional wheels that can be reliably modeled by my method are those that have free rolling rollers on their circumference, shaped in an attempt to achieve smooth ride and small contact point fluctuations. Further plans include verifying and calibrating the model to a real mobile platform.

5. Conclusion

In this paper a method for modifying an existing, widely used tire model was presented. By this modification the model is able to describe the force generation of a class of omnidirectional wheels. The wheel model was implemented in Modelica in two different embodiments, for two different platforms. The usability of the models was demonstrated by applying them on an industrial forklift model. The model was created with simplicity and ease of use in mind, so some effects of smaller importance are not modeled. Some hints for the future extension of the wheel model were given at the end of this article.

The author would like to express his appreciation to Dr. Tamás Juhász and people at the IFF Fraunhofer Magdeburg who helped him with Modelica and received him at their lab. He would also like to thank Dr. László Vajta for valuable suggestions and inspiration for this work.

References

[1] R. Ahmad, P. Toonders, M.J.D. Hayes, and R.G. Langlois. *Atlas mecanum wheel jacobian empirical validation.* In *CSME International Congress*, Winnipeg, MA, Canada, 2012.

[2] Magnus Jonason Bjärenstam and Michael Lennartsson. Master's thesis, Lund University, Department of Automatic Control, 2012.

[3] Raymond M. Brach and R. Matthew Brach. *Tire models for vehicle dynamic simulation and accident reconstruction.* Technical report, Brach Engineering, 2009. SAE Technical Paper.

[4] Jochen Brunhorn, Oliver Tenchio, and Raúl Rojas. Robocup 2006: *Robot soccer world cup x. chapter A Novel Omnidirectional Wheel Based on Reuleaux-Triangles*, pages 516–522. Springer-Verlag, Berlin, Heidelberg, 2007.

[5] Kyung-Seok Byun and Jae-Bok Song. Design and construction of continuous alternate wheels for an omnidirectional mobile robot, *Journal of Robotic Systems*, 20(9):569–579, 2003.

[6] Douwe Dresscher, Yury Brodskiy, Peter Breedveld, Jan Broenink, and Stefano Stramigioli. *Modeling of the youbot in a serial link structure using twists and wrenches in a bond graph.* In *Proceedings of SIMPAR 2010 Workshops*, pages 385–400, Germany, November 2010. SIMPAR.

[7] W. Hirschberg, G. Rill, and H. Weinfurter. *Tire model TMeasy. VEHICLE SYSTEM DYNAMICS*, 45(S):101–119, 2007.

[8] Bengt Erland Ilon. *Wheels for a course stable selfpropelling vehicle movable any desired direction on the ground or some other base*, 1975. US Patent No. 3876255.

[9] Giovanni Indiveri. *Swedish wheeled omnidirectional mobile robots: Kinematics analysis and control. IEEE Transactions on Robotics*, 25:164 – 171, 2009.

[10] Viktor Kálmán and László Vajta. *Designing and tuning a brake assistant for omnidirectional wheels, Periodica Polytechnica* 56:(4), 2012.

[11] Viktor Kálmán and László Vajta. *Slip based center of gravity estimation for transport robots.* In *Factory Automation*, pages 50–55, Veszprém, Hungary, May 21-22. 2012. University of Pannonia.

[12] Masaaki Kumaga and Takaya Ochiai. *Development of a robot balanced on a ball - application of passive motion to transport.* In *Robotics and Automation, 2009. ICRA '09. IEEE International Conference on*, pages 4106 –4111, may 2009.

[13] T.B. Lauwers, G.A. Kantor, and R.L. Hollis. *A dynamically stable single-wheeled mobile robot with inverse mouse-ball drive.* In *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, pages 2884 – 2889, may 2006.

[14] P. Muir and C. Neuman. *Kinematic modeling for feedback control of an omnidirectional wheeled mobile robot.* In *Robotics and Automation. Proceedings. 1987 IEEE International Conference on*, volume 4, pages 1772 – 1778, mar 1987.

[15] Martin Otter and Hilding Elmqvist. *Modelica - Language, Libraries, Tools, Workshop and EU-Project RealSim.* German Aerospace Center, Dynasim AB, June 2001.

[16] Hans B. Pacejka. *Tyre and vehicle dynamics.* Butterworth-Heinemann, 2002.

[17] F.G. Pin and S.M. Killough. *A new family of omnidirectional and holonomic wheeled platforms for mobile robots. Robotics and Automation, IEEE Transactions on*, 10(4):480 –489, aug 1994.

[18] Prof. Dr.-Ing. Georg Rill. Vieweg+Teubner Verlag, 1994.

[19] Daniel Ruf and Jakub Tobolár. Omnidirektionale fahrzeuge für schwerlasttransport in produktion und logistik. *Logistik und Verkehr in Bayern*, 12:34–35, 2011.

[20] D. Stonier, Se-Hyoung Cho, Sung-Lok Choi, N.S. Kuppuswamy, and Jong-Hwan Kim. *Nonlinear slip dynamics for an omniwheel mobile robot platform.* In *Robotics and Automation, 2007 IEEE International Conference on*, pages 2367 – 2372, april 2007.

[21] J. Tobolár, F. Herrmann, and T. Bünte. *Object-oriented modelling and control of vehicles with omni-directional wheels.* In *Computational mechanics 25th conference with international participation*, Hrad Nectiny, Czech Republic, November 9-11 2009.

[22] H.-J. Unrau and J. Zamow. *TYDEX-Format, Description and Ref. ManualTYDEX-Format, Description and Ref. Manual.* Initiated by the TYDEX Workshop, release 1.3 edition, Sept. 1997.

[23] II Williams, R.L., B.E. Carter, P. Gallina, and G. Rosati. *Dynamic model with slip for wheeled omnidirectional robots. Robotics and Automation, IEEE Transactions on*, 18(3):285 –293, jun 2002.

[24] Dirk Zimmer and Martin Otter. *Real-time models for wheels and tyres in an object-oriented modelling framework. Vehicle System Dynamics*, 48(2):189–216, 2010.