Omnidirectional wheeled mobile robots: wheel types and practical applications

Kiattisin Kanjanawanishkul

Mechatronics Research Unit,
Faculty of Engineering,
Mahasarakham University,
Kamriang, Kantharawichai,
Mahasarakham, 44150, Thailand
Email: kiattisin.k@msu.ac.th

Abstract: Omnidirectional wheeled mobile robots (OWMRs) have gained increasingly popularity because they can move into any direction, while their orientation can be pointed to any angles. Thus, the aims of this paper are to update a literature review of OWMRs and to categorise interesting research papers according to wheel types, wheel arrangements, and their practical applications. Wheel types are divided into special omnidirectional wheels and steerable conventional wheels. Advantages and disadvantages of each type of OWMRs are also pointed out in order to help robotic designers to choose an appropriate wheel mechanism. Then, practical applications are presented to show the usefulness of OWMRs.

Reference to this paper should be made as follows: Kanjanawanishkul, K. (2015) 'Omnidirectional wheeled mobile robots: wheel types and practical applications', *Int. J. Advanced Mechatronic Systems*, Vol. 6, No. 6, pp.289–302.

Biographical notes: Kiattisin Kanjanawanishkul received his BEng in Electrical Engineering from Prince of Songkla University, Thailand in 2000. He received his MSc in Mechatronics from University of Siegen, Germany in 2006. He received his PhD in Computer Science from University of Tuebingen, Germany in 2010. Since 2010, he has been employed at the Faculty of Engineering, University of Mahasarakham, Thailand. His current research interests include cooperative and distributed control, model predictive control, omnidirectional mobile robots, and robotic motion control.

1 Introduction

A wheeled mobile robot without non-holonomic constraints can move instantaneously in any direction regardless of current position and orientation. It can also simultaneously attain any desired orientation. This capability is widely known as omnidirectional mobility which can be realised using omnidirectional wheeled mobile robots (OWMRs) (Campion et al., 1996; Indiveri, 2009). They have remarkable advantages over more common design platforms like car-like robots and differential drive robots in terms of dexterity and maneuverability in environments congested with obstacles and narrow spaces, such as, warehouses, supermarkets, and manufacturing floor.

Until now, various kinds of omnidirectional mobile robots have been proposed: legged robots, ball wheeled robots, special wheeled robots, and so on. However, in this paper, we focus only on wheeled mobile robots since their maximum speed is much higher and they are less complex. In addition, their inverse kinematics solution for path planning is simpler. Due to these district advantages, throughout the past few decades, there have been a plenty of

design strategies and construction of OWMRs and there have been a wide range of applications that OWMRs have been used successfully. Thus, the main aims of this paper are to update a literature review of OWMRS and to categorise interesting research papers according to wheel types, wheel arrangements, and their practical applications.

This paper is not the first one that gives a literature review of OWMRs. Muir and Neuman (1986) formulated the kinematic equations-of-motion of wheeled mobile robots and surveyed existing wheeled mobile robots; however their paper was published in 1986. Adascalitei and Doroftei (2011) addressed practical applications for OWMRs with Mecanum wheels but they did not focus other kinds of OWMRs. Kalman (2013) focused only on a configurable omnidirectional wheel model used for dynamic simulation and parameter tuning of OWMRs. Parmar and Savant (2014) addressed merely how to select the wheels of robots. Jacobs et al. (2014) described strength and weakness of each wheel mechanism but literature survey was not given.

A variety of designs of omnidirectional wheels can be broken into two basic types: one type is using special wheels with or without special mechanisms, and the other type is conventional wheels. In this paper, we address only the following omnidirectional wheels: special wheels including universal wheels, and Mecanum wheels, and conventional wheels divided into powered castor wheels (PCWs) and steerable standard wheels.

The rest of the paper is organised as follows: Sections 2 and 3 deal with literature survey of an OWMR equipped with special omnidirectional wheels and steerable conventional wheels, respectively. Advantages and disadvantages of each type are also pointed out in order to help robotic designers to choose an appropriate wheel mechanism. In Section 4, some practical applications are presented to show the usefulness of OWMRs. Finally, conclusions are drawn in Section 5.

2   Special omnidirectional wheels

A concept of special wheel design is that active traction is attained in the wheel's driving direction and passive motion is allowed in direction that is not parallel to the wheel's driving direction. That is each wheel has some axis which it can freely rotate. By combining a number of such wheels, a velocity can be then induced by the other wheels in this direction.

There are many different special wheel mechanisms created to achieve omnidirectional motion. However, in this paper, we address commercially available wheel mechanisms, i.e., universal wheels and Mecanum wheels. Note that due to discontinuous wheel contact points and discontinuous changes in wheel velocity, all of special wheel mechanisms, except for some type, are a main source of vibration. It can be reduced as the robot consists of more wheels. However, suspension is needed to keep all of the wheels contact with uneven ground when four or more wheels are used. This results in complicating the design.
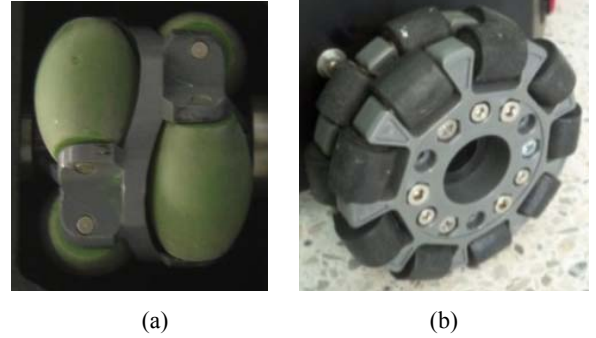
2.1   Universal wheels

A universal wheel or an omni wheel is designed in such a way that there are a number of small passive rollers mounted on the periphery of a normal wheel as seen in Figure 1. The axes of these rollers are perpendicular to that of the wheel. The wheel is driven in a normal fashion, while the rollers can roll orthogonally to its driving direction freely. By using several universal wheels distributed around the periphery of a robot platform, forces applied at each wheels can be combined to provide omnidirectional mobility.

In general, the universal wheel with six passive rollers forming a circle [see Figure 1(a)] or the universal wheel with two rows of the rollers [see Figure 1(b)] is used to reduce discontinuities of the roller. However, this makes control and odometry more complicated since the contact point of the wheel is shifted between the inner and outer rows of rollers. If the distance between both rows of rollers
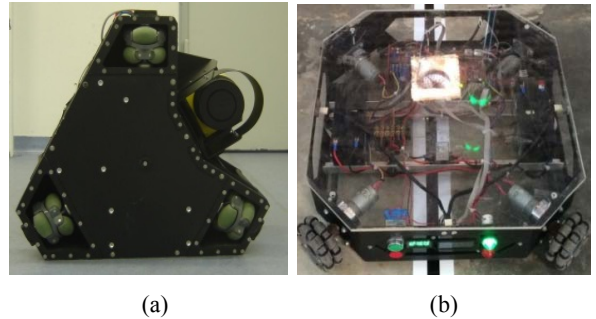
is much smaller than the radius of the robot, this problem is not severe.

Figure 1   A universal wheel with (a) poly rollers and (b) two rows of rollers (see online version for colours)

(a)   (b)

Theoretically, a three-wheeled platform such as that shown in Figure 2(a) provides greater traction since the reaction force is distributed via only three points. This design is mechanically simpler and all wheels can contact with the ground at all times on uneven surfaces. But it may have a stability problem due to the triangular points with the ground, particularly when it moves on a ramp with the high centre of gravity. Thus, a four-wheeled robot such as that illustrated in Figure 2(b) is desirable.
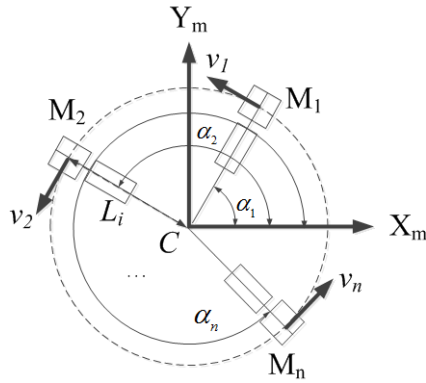
Figure 2   An OWMR with (a) three universal wheels used for the RoboCup competition and (b) four universal wheels used for object transport (see online version for colours)

(a)   (b)

To understand how an OWMR with universal wheels behaves and moves through space, its kinematics has to be described. For n wheels, we obtain the following expression for the relationship between the wheel's translational speed $(v_1, \ldots, v_n)^{\mathrm{T}}$ and the OWMR's speed (u, v, ω) (see Figure 3):
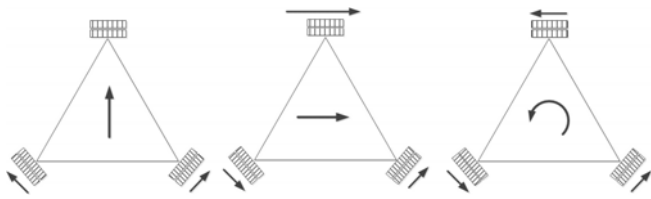
$$\begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} -\sin\alpha_1 & \cos\alpha_1 & L_1 \\ -\sin\alpha_2 & \cos\alpha_2 & L_2 \\ \vdots & \vdots & \vdots \\ -\sin\alpha_n & \cos\alpha_n & L_n \end{bmatrix} \begin{bmatrix} u \\ v \\ \omega \end{bmatrix} \quad (1)$$

where α_i, $i = 1, \ldots, n$ is the angle of the motor axis measured relative to the X_m-axis direction of the OWMR. L_i, $i = 1, \ldots, n$ denotes distance from the centre of mass to the centre of wheel i. u, v are local linear velocity components in the directions of the X_m-axis and Y_m-axis of the moving frame, respectively, while ω represents the angular velocity.

Figure 3 Some movements of a three-wheeled OWMR

2.1.1 Three universal wheels

As shown in Figure 2(a), an OWMR equipped with three independent driving wheels equally spaced at 120 degrees from one to another. When the motor connected to each wheel is activated, we obtain three traction forces from the motors, which add up to a translational force and a rotational torque. Figure 4 shows some movement examples of an OWMR, which depend on direction and velocity of each wheel.

Figure 4 Some movements of a three-wheeled OWMR

Three-wheeled OWMRs have been constructed by a large number of research groups. For example, the trajectory tracking control problem has been solved by a GA-based fuzzy controller (Wong et al., 2005), a trajectory linearisation control method (Liu et al., 2008), an adaptive backstepping control method (Huang and Tsai, 2008), a passivity-based control formulation (Velasco-Villa et al., 2010), a state feedback model predictive controller (Araujo et al., 2011), a differential sliding mode tracking controller (Dinh et al., 2012), a model predictive control scheme with friction compensation (Barreto et al., 2014), a nonlinear model predictive control scheme (Timothy et al., 2014). The other basic motion is path following control. This problem has been solved by a model predictive controller (Kanjanawanishkul and Zell, 2009) and a fuzzy logic controller (Pai et al., 2012).

Likewise, Loh et al. (2003) addressed mechatronics design and kinematic modelling of a singularityless OWMR. DaneshPanah et al. (2007) presented an idea of separating odometry sensors from the driving wheels. Errors due to slippage in the time of acceleration were reduced. Stonier et al. (2007) studied the fundamental nonlinear slip dynamics. Ushimia and Aoba (2012) improved dead reckoning using a two-wheel caster type of odometer. Trajectory generation and path planning have also been

addressed by Kalmár-Nagy et al. (2004), Balkcom et al. (2006), Williams and Wu (2010). Recently, Tavakoli and Viegas (2014) implemented Omniclimbers which were climbing robots equipped with three magnetic omnidirectional wheels.

2.1.2 Four universal wheels

Figure 5 shows an OWMR equipped with four independent driving wheels equally spaced at 90 degrees from one to another. Notice that the main difference between both diagrams is that the axis of the moving frame is differently defined. In Figure 5(a), α_i, where $i = 1, 2, 3, 4$ are equal to 45°, 135°, −135°, and −45°, respectively, while in Figure 5(b), α_i, where $i = 1, 2, 3, 4$ are equal to 0°, 90°, 180°, and −90°, respectively.
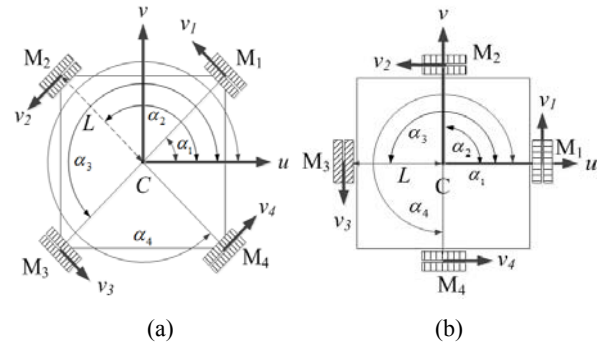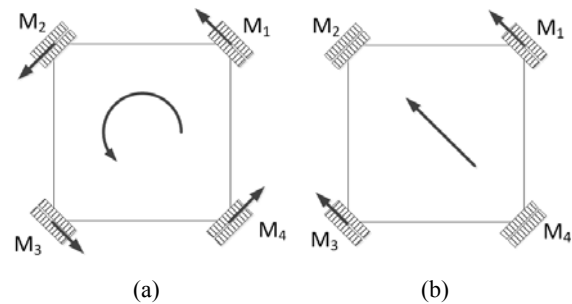
Figure 5 Geometric parameters of the four-wheeled OWMR where (a) its four wheels are on all four corners at 45-degree angles and (b) its four wheels are on the opposite side

(a)   (b)

Figure 6 shows some examples of movements using a four-wheeled OWMR. Translational motion along any direction can be produced by composition of the translational motion along x-axis and y-axis. The rotational motion about z–axis is driven by all four wheels rotating in the same direction. However, the robots have one excess DOF. This redundancy causes such control problems that the unique output should be determined.

Figure 6 Some examples of movement of a four-wheeled OWMR, (a) CCW rotation (b) move forward-left
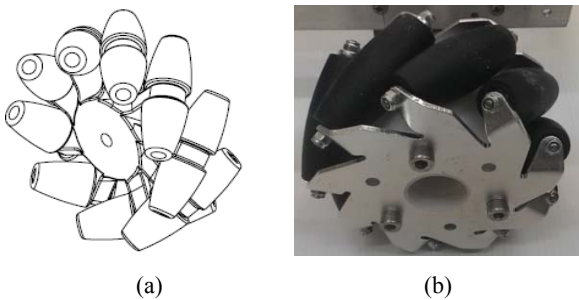

(a)   (b)

To cope with such a redundancy problem, the solutions were proposed by Asama et al. (1995), Wilson et al. (2001), Rojas and Forster (2006). Other motion control methods have also been proposed, e.g., a T-S fuzzy path controller (Shing et al., 2006), a fuzzy-based trajectory tracking control law (Li et al., 2008), a self-tuning PID control method (Qi et al., 2009), a model predictive controller (Conceicao et al., 2010), a sliding mode controller (Chen et al., 2014).

Trajectory generation and path planning have also been addressed by Purwin and D'Andrea (2006), Leng et al. (2008) and Lupian and Rabadan-Martin (2009). Conceicao et al. (2006) presented three methods of parameters identification related to dynamic equations. Song and Byun (2006) presented an OWMR with steerable omnidirectional wheels called continuous alternate wheels (CAW). This robot can operate in either omnidirectional or differential drive modes, depending on the drive conditions.

2.2 Mecanum wheels

The Mecanum (or Swedish) wheel is sometimes called the Ilon wheel after its Swedish inventor, Bengt Ilon, who invented it in 1973 when he was an engineer with the Swedish company Mecanum AB (Ilon, 1975). The Mecanum wheel is based on the concept of a central wheel with a series of free rollers placed at an angle around the periphery of the wheel. The rollers are placed such that the overall side profile of the wheel is circular (see Figure 7). The angled roller translates a portion of the force in the driving direction of the wheel to force normal to the wheel direction. The angle between rollers axis and central wheel can have any value but in the case of the conventional Mecanum wheel, it is 45°, as seen in Figure 7.

Figure 7   (a) Drawing of a Mecaunum wheel and (b) a physical Mecanum wheel

(a)   (b)

The Mecanum wheel has three DOFs (Song and Byun, 2006). But only one DOF is actuated with a motor, whereas the others are passive to detach constraint forces in order to attain omnidirectional motion. The platform configuration of the robot may be square or rectangular and one wheel is located at each corner of the chassis (two mirrored pairs), as illustrated in Figure 8. The resulting combination of all forces produced by each individual wheel yields a total force vector that moves the robot in the desired direction. To describe how an OWMR with Mecanum wheels behaves and moves through space, the following expression for the relationship between the wheel's translational speed (v_{1w},

v_{2w}, v_{3w}, v_{4w})^T and the OWMR's speed (u, v, ω) can be obtained (see Figure 8):

$$\begin{bmatrix} v_{1w} \\ v_{2w} \\ v_{3w} \\ v_{4w} \end{bmatrix} = \begin{bmatrix} 1 & 1 & l_a + l_b \\ 1 & -1 & -l_a - l_b \\ 1 & 1 & -l_a - l_b \\ 1 & -1 & l_a + l_b \end{bmatrix} \begin{bmatrix} u \\ v \\ \omega \end{bmatrix} \qquad (2)$$

where l_a and l_b are the distance from the wheel axis to the robot's body centre in the x-and y-directions, respectively.

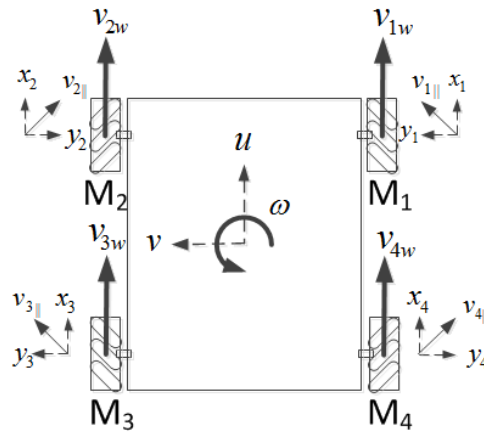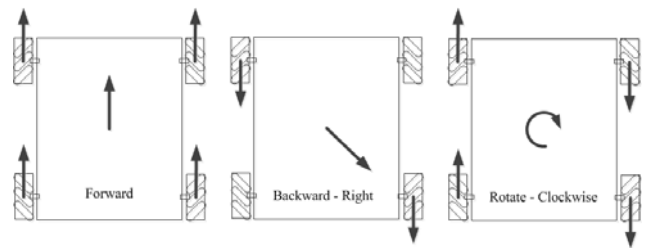**Figure 8**   Velocity vectors created by motors connected to Mecanum wheels

Figure 9 shows some of robot motion according to the direction and angular speed of the wheels. Combinations of these four wheel motions allow for vehicle motion in any direction with any vehicle rotation.

Figure 9   Robot motion according to the direction and angular speed of the wheels

However, this system is over-actuated since there are four variables to control three DOFs. This issue may lead to creating conflicts in the actuation. Thus, some form of a controller is needed to produce satisfactory motion.

Many researchers have designed and constructed OWMRs with Mecanum wheels for various purpose and applications over the past few decades. For example, Diegel et al. (2002) improved the Mecanum wheel by adjusting the angle of the peripheral rollers to best suit the direction of travel. Koestler and Braunl (2004) developed two different Mecanum-wheeled OWMR with rims and without rims. The OWMR with rimless Mecanum wheels and shocks absorbers can move on softer surface and uneven surface. Ramirez-Serrano and Kuzyk (2010) proposed two modified Mecanum wheel designs, i.e., elliptical Mecanum double

wheel and semicircular Mecanum double wheel, to overcome the difficulties when moving on rough terrains.

Dickerson and Lapin (1991) explored three aspects of the Mecanum wheeled vehicles, the ability to maneuver in congested spaces, the kinematics of wheel design, and considerations for wheel loading and traction. Ransom et al. (2008) developed a pressurised, habitable rover, called MarsCruiserOne, for the exploration of planetary surfaces. Hsu et al. (2012) presented the intelligent robotic wheelchair (*i*RW) using four Mecanum wheels.

Muir and Neuman (1987) applied the kinematic methodology to dead reckoning, wheel slip detection and feedback control of an OWMR, called Uranus. Nagatani et al. (2000) implemented a robust navigation in indoor and outdoor environment. To cope with the problem of wheel slippage, odometry was fused with visual dead-reckoning to improve the estimated vehicle position. Cooney et al. (2004) tested the path following performance of the robot in both open-loop and closed-loop modes and the optical mice were used for giving positional feedback for closed-loop control and dead-reckoning for navigation. Tlale and Villiers (2008) addressed the optimum vehicle motion in different situations for collision avoidance and task achievement. Killpack et al. (2010) presented a system with a downward-facing camera and light ring to provide robust visual odometry estimates.

2.3 Other special wheels and special mechanisms

Several special mechanisms and several special wheels have been invented to achieve omnidirectional motion. They may offer higher payload, less vibration, less complication, higher efficiency, or mobility on uneven ground. For example, Watanabe (1998) derived a dynamic model of an OWMR equipped with three lateral orthogonal-wheel assemblies and he also proposed a control scheme with a PID method, a fuzzy model method, and a stochastic fuzzy servo method. Pin and Killough (1999) presented a three orthogonal-wheel platform. Two possible assembly configurations of these wheels, labelled the longitudinal and lateral assemblies, were discussed. Mourioux et al. (2006) addressed an OWMR using three motorised axles with two spherical orthogonal wheels. These wheels were used on two mechanical structures: SM1 and SM2. Ma et al. (2012) developed a wheeled mechanism, named as MY wheels-II, based on the sliced ball structure. Djebrani et al. (2012) developed a controller for an omnidirectional mobile manipulator equipped with three motorised axles with two spherical orthogonal wheels.

Jung et al. (2001) developed OmniKity-III consisting of a two-wheeled differentially driven mobile robot base and a revolute joint that supports the main body on the base. Damoto et al. (2001) focused on a transport vehicle, called Vuton-II. This robot was composed of three or more omni-disc mechanisms that ensure that each wheel of the omni-disc assembly was always aligned in the same direction. Tadakuma et al. (2004) developed an OWMR with step climbing capability, called VmaxCarrier2. It consisted of the Omni-Disc2, a bent pneumatic actuator, and

a pneumatic system. Then, Tadakuma et al. (2007) further developed a novel spherical wheel shape, called omni-ball which was formed by two passive rotational hemispherical wheels and one active rotational axis. After that, Tadakuma et al. (2008) proposed a crawler mechanism for sideways motion. It was of circular cross-section and had active rolling axes at the centre of the circles.

Yamashita et al. (2001) proposed a seven-wheeled OWMR that can move on the unevenness and pass over steps. They adopted a passive suspension system that enabled the robot to change the shape of the robot body in proportion to ground states without using actuators and sensors. Chen et al. (2002) presented an off-road OWMR which can run on an uneven road and obstacles. The robot was constructed with four crawler-oller-motor units. Zhang et al. (2012) presented a compact omnidirectional permanent-magnetic wheeled wall-climbing microrobot. Its mechanism was realised by a set of steering gears and three standard permanent-magnetic wheels.

West and Asada (1997) established two fundamental requirements of functioning ball wheel designs: one was the translational form closure requirement for holding a spherical tire, and the other was the non-overconstraint requirement to allow each ball to rotate in two directions. Kumaga and Ochiai (2009) proposed a robot balanced on a ball. It was equipped with three omnidirectional wheels with stepping motors that drive the ball and two sets of rate gyroscopes and accelerometers as attitude sensors. Nagarajan et al. (2014) presented a ballbot, which was a human-sized dynamically stable mobile robot that balances on a single ball.

Ferriere and Raucent (1998) presented an OWMR consisting of a sphere driven by a classical universal wheel. Ball et al. (2010) presented a spherical omnidirectional drive mechanism using a single motor to drive a point on the great circle of the sphere parallel to the ground plane. Three mechanisms located 120° apart provided a stable drive platform for a mobile robot. Vrunda et al. (2010) analysed a spherical-wheeled mobile robot rolling on a plane for feasible path planning and feedback control algorithms. Ghariblu et al. (2011) implemented an OWMR using three spherical wheels driven by classical omni-wheels. Chen et al. (2012) presented an omnidirectional spherical robot, called Omnicron. Three omnidirectional wheels were installed inside the spherical shell and controlled independently.

Wada and Asada (1999) proposed a variable footprint mechanism, where four independent servo motors driving the four ball wheels allowed the vehicle to move in an arbitrary direction as well as to change the footprint. Endo and Nakamura (2005) developed an OWMR with a spherical tire. It moved by rolling a spherical tire and balancing on it. Ishigami et al. (2012) invented anisotropic friction wheels that enabled a vehicle to realise omnidirectional motion. Hyunseok et al. (2013) proposed an OWMR with one spherical wheel. It was composed of two stepping motors, a spherical wheel covered by a ball bearing, a weight balancer, and ball plungers.

3   Steerable conventional wheels

Robots composed of special wheels usually have some disadvantages. For example, they have lower load capacity compared with conventional wheels, because they typically adopt fragile rollers to support the loads. Their mechanisms are likely to have poor ground clearance because the use of small peripheral rollers and/or the mechanism arrangement leaves some of the support structure close to the ground. Their special wheels cannot be rotated on the dirty floors because dirt can be squeezed into the roller and block the movement. They are also limited to hard even surfaces due to the small roller diameters. Using steerable conventional wheels can overcome these shortcomings, making them very interesting. In particular, steerable conventional wheels with pneumatic tires can travel on uneven floors and have higher load capacity.

In general, conventional wheels cannot move sidewise because of non-holonomic constraints. But they can achieve near-omnidirectional motion by adding the wheel steering mechanism. Thus, they consist of at least two independently steered and independently driven wheels. As shown in Figure 10, a wheel is mounted to an orthogonal steering actuator which can rotate the wheel to orient it in any planar direction. With two or more such wheels near-omnidirectional mobility can be achieved.

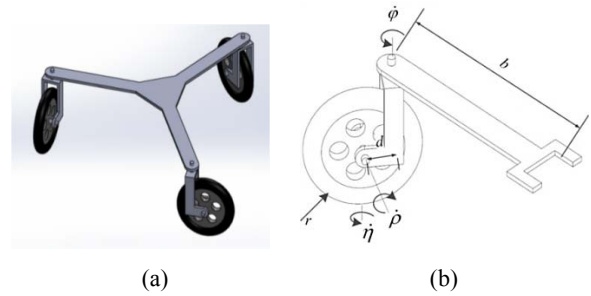**Figure 10**   Steerable conventional wheel, (a) PCW and (b) steerable standard wheel

In the literature, PCWs like the one shown in Figure 10(a) or steerable standard wheels such as that seen in Figure 10(b) are popularly used to achieve this near omnidirectional mobility. But controlling numerous PCWs or steerable standard wheels to create a synchronised mobile base motion is very challenging. Due to actuation redundancy, force distribution and slip minimisation algorithms are required to fix the slippage problem. The second challenge is to derive a dynamic model of wheel-ground interaction. The accurate model is critical for applying advanced control laws to the motion system.

3.1   Powered castor wheels

PCWs or active castor wheels are capable of steering around a vertical axis, but the vertical axis of rotation in a castor wheel does not pass through the ground contact point. Figure 11(b) depicts a PCW with some geometric parameters.

Figure 11   (a) An OWMR with three PCWs and (b) a PCW with some geometric parameters

For a three-PCW robot as shown in Figure 11, there are six independent joint variables, i.e., three driving variables $(\dot{\rho}_1, \dot{\rho}_2, \dot{\rho}_3)$ and three steering variables $(\dot{\varphi}_1, \dot{\varphi}_2, \dot{\varphi}_3)$. We can define three minimum coordinates out of six joint variables since the OWMR has three DOFs. Due to the space limit, the kinematic model of the PCW robot can be found in the work of Jung et al. (2007).

Furthermore, one major drawback of the PCW design is the high friction and scrubbing during the steering when the wheel is actively twisted around a vertical axis. This reduces positioning accuracy and increases power consumption and tire wear, especially for heavy vehicles. To reduce these problems, an active offset split caster (ASOC) module with a dual wheel has been designed. The concept design is commonly found in the aircraft front landing module.

Analysis of both PCW and ASOC designs has been studied extensively. For example, an OWMR has been equipped with two PCW modules proposed by Yamada et al. (2001), with three PCW mechanisms developed by Wada (2006), Jung et al. (2007), Zhao et al. (2009) and with four PCW mechanisms investigated by Holmberg and Khatib (2000) and Li et al. (2005).

An OWMR using four ASOC modules has been presented by Udengaard and Iagnemma (2009) and Ishigami et al. (2011), while an OWMR using two ASOC modules and two conventional castors has been proposed by Yu et al. (2004). Kinematic analysis on an OWMR with multiple ASOC modules has been studied by Lee et al. (2007). Wada et al. (2000) presented a dual-wheel-castor configuration, i.e., two castor wheels driven by two independent motors and one rotational actuator. Chung et al. (2010) designed an OWMR with dual offset steerable wheels with orthogonal velocity components. Inoue et al. (2013) designed OWMRs with two active-caster robotic drive with ball transmission (ACROBAT) wheels.

3.2   Steerable standard wheels

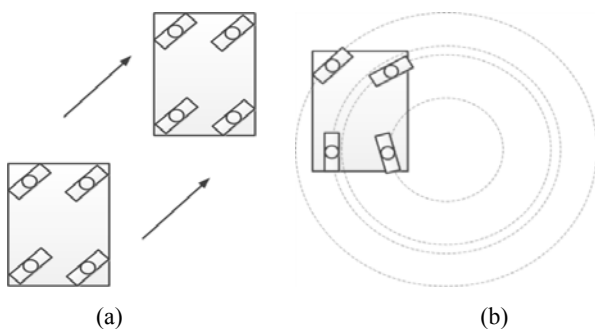Each motor/wheel module consists of one driving motor and one steering motor and each is controlled independently. However, two or more wheels may be steered together via drive trains. For example, one of the most famous wheel mechanisms is synchro drive. It has three driven and steered wheels and only two motors. One translation motor sets the speed of all three wheels together, and one steering motor

spins all the wheels together about each of their individual vertical steering axes. The robots with mechanically coupled pairs of steered wheels have been modelled and controlled easily; however, modelling and controlling of robots with independently steered wheels are very challenging. This structure has potential to turn unlimitedly and independently, thus the maneuverability of robots can be increased by proper coordination of the orientation of wheels. A special type of motion is linear translation where all the wheels are oriented in the same direction and all have the same speed [see Figure 12(a)]. With turning in an arc, each wheel must be tangent to a circle in a set of concentric circles to avoid skidding, as shown in Figure 12(b).

To maximise maneuverability, in the literature, there are many possibilities of wheel mechanism configuration and modelling. For example, an OWMR composed of three individually driven and steered wheels has been proposed by Kim et al. (2003), equipped with four steerable standard wheels constructed by Yavin (2003), Lauria et al. (2006), Lam et al. (2009), Connette et al. (2010), Selekwa and Nistler (2011), Dietrich et al. (2011), Borrero et al. (2012), Oftadeh et al. (2014) and Berntorp et al. (2014). Betourne and Campion (1996) considered robots equipped with at least three independently steerable wheels. Moore and Flann (2000) and Berkemeier and Ma (2005) developed an omnidirectional vehicle with six smart wheels, each of which can be independently controlled to a prescribed drive speed and steering angle. Mori et al. (1999) designed the ODV9, that had four wheel modules, with each wheel module incorporating a motor, brake, and a wheel. Each wheel modules had a wide steering range and moved independently resulting in different running modes. Thuilot et al. (1996) dealt with state feedback control of mobile robots equipped with several steering wheels.

Figure 12 Some motions of an OWMR equipped with steerable standard wheels, (a) linear translation and (b) turning in an arc

(a)   (b)

4 Practical applications

The OWMR offers exceptional mobility. It can reach restricted spaces in factories and plants easily. These remarkable advantages will save time and difficulties. Thus, this section presents some interesting practical applications using the benefit of omnidirectional mobility, including wheelchairs and healthcare vehicles for the handicapped or the elderly, RoboCup competitions, and material transportation and cooperative manipulation.

4.1 Wheelchairs and healthcare vehicles

Since the number of elderly in need of care is increasing dramatically today, the intelligent service robots may assist people in their daily living activities. For example, Wada and Asada (1999) proposed an OWMR equipped with a reconfigurable mechanism for varying the footprint and applied to wheelchairs. Wada (2007) improved wheelchair step-climbing and maneuverability by introducing a 4WD. It consisted of a pair of normal wheels in back and a pair of universal wheels in front and they were connected by a transmission and driven by a common motor to make them rotate together. Also, Zou (2011) presented a three-wheeled omnidirectional mobile home care robot equipped with an indoor positioning system, a robot arm and a network camera. Infrared sensors were placed around the robot for obstacle avoidance. Hsu et al. (2012) presented the *i*RW equipped with four Mecanum wheels. Five operation modes were developed: obstacle avoidance, joystick mode, handlebar mode, teleoperation, and indoor navigation.

For additional mobility support, Tan et al. (2012) developed a cushion robot with four omni wheels to support indoor movement of the elderly. An adaptive path-following controller that can estimate the load and a shift of the centre of gravity on-line was designed. Jiang et al. (2014) developed an omnidirectional walker for people who have walking problems. They also proposed a fuzzy-learning method to recognise a user's directional intention to control the omnidirectional walker. Recently, Fukuda et al. (2015) designed an intelligent cane robot for helping the elderly and handicapped walking. A three-wheeled omnidirectional platform was used to enable the cane robot moving in the most of the living environment.

4.2 RoboCup competitions

The annual international RoboCup competition, where teams of autonomous robots compete in soccer-like games, is an example where OWMRs have been widely used and extremely successfully (Weitzenfeld et al., 2014). OWMRs can move from one place to another with independent linear and angular velocities. As a result, the number of maneuvers is reduced and consequently the game strategy can be simplified.

Since the first RoboCup tournament has been imitated, there have been a large number of publications on this research topic. Here only some interesting papers are reviewed. Wilson et al. (2001) presented a dynamic model and a simple PD control for a redundant omnidirectional RoboCup goalie. Egorova et al. (2005) described the F180 team, the FU-Fighters, which won first place in the small size league competition in 2004 and 2005. A hierarchy of reactive behaviours was used to control the robots. They also used a neural network for learning the robot's response to the commands. DaneshPanah et al. (2007) presented an OWMR where omnidirectional navigation system,

omni-vision system and a novel kicking mechanism were combined to create a comprehensive soccer player robot. Williams and Wu (2010) implemented a method of obstacle-avoidance motion planning in dynamic environments to the Ohio University RoboCup robot.

Trajectory generation and path planning for the RoboCup competitions were also addressed by Kalmar-Nagy et al. (2004), Purwin, O., D'Andrea (2006), Leng et al. (2008) and Lupian and Rabadan-Martin (2009).

Conceicao et al. (2006) presented three methods of parameters identification related to dynamic equations. Rojas and Forster (2006) showed a method that computed a set of optimal motor forces and speeds to avoid wheel slippage of an OWMR they used in the small size and middle size RoboCup robots. Heinemann et al. (2006) presented a combined Monte-Carlo localisation based on images from an omnidirectional camera system and a tracking algorithm for the Attempto RoboCup Robot Team. Qi et al. (2009) applied parameter self-tuning PID control method combining fuzzy control with traditional PID control to a soccer robot platform. Hamidreza et al. (2010) developed a three-wheeled OWMR with a novel kicking system that enabled loop and varied shooting power.

4.3 Material transportation and cooperative manipulation

Flexible material handling and transport has become an integral part of modern manufacturing. Recently, OWMRs attract much attention from researchers since they are able to move sideways making them suitable for this task, in particular, in congested environments. Thus, in this subsection, automated guided vehicles (AGVs) with omnidirectional mobility and mobile manipulators are reviewed since they are both subject to ongoing research.

Yang et al. (2000) presented a method for reliable, real-time obstacle avoidance for an OmniMate vehicle consisting of two trucks connected by a compliant linkage. Diegel et al. (2002) combined a set of Mecanum wheels with a set of conventional wheels so that when rough terrain was detected, a set of pneumatics actuators changed Mecanum wheels to conventional wheels. Tlale and Villiers (2008) addressed the optimum vehicle motion in different situations for object/collision avoidance and task achievement using a combination of different driven wheels. Kim et al. (2012) proposed localisation of an omnidirectional AGV with Mecanum wheels using encoders, gyro and accelerometer. Recently, Heß et al. (2013) developed a Linux-based control framework for Mecanum-based omnidirectional AGVs.

Asada et al. (1996) developed cooperative mobile robots for mutual transportation including a holonomic omnidirectional platform and a forklift mechanism. Damoto et al. (2001) invented the Omni-Disc omnidirectional wheels for the Vuton-II, an omnidirectional transport vehicle. Tadakuma et al. (2004) developed an OWMR with step climbing capability, called VmaxCarrier2, which can be used as a transportation vehicle in cluttered environments. Kumaga and Ochiai (2009) showed ability of a robot balanced on a ball to transport loads in any direction. Goller et al. (2009) presented the haptic-based control of an interactive behaviour operated shopping trolley (InBOT). It can relieve customers from the burden of pushing the shopping cart, especially if the cart is heavily loaded or the customer is elderly or handicapped. Schulze et al. (2011) developed an omnidirectional AGV that was optimised for the transportation of small goods.

OWMRs for material transportation are currently commercially available. For example, Omnix Technology Systems, Inc. (http://www.omnixtechnology.com) has developed a variety of Omni-transporters equipped with Mecanum wheels. Airtrax (http://www.airtrax.com) has developed an Omni-Directional Lift Truck using Mecanum wheels. KUKA Omnimove (http://www.kuka-omnimove.com) has proposed a holonomic base which allows for highly controlled mobility.

Mobile manipulators have also been addressed by several research groups. For example, Holmberg and Khatib (2000) developed a mobile manipulator equipped with powered castors. Huang and Tsai (2008) showed an experimental mobile service robot consisting of an autonomous mobile platform and a manipulator to perform a fetch-and-carry task. Killpack et al. (2010) presented a visual odometry system for a mobile manipulator with a Mecanum omnidirectional base. Connette et al. (2010) implemented a controller with predictive potential for the mobile base of Care-O-bot 3 equipped with lightweight arms. Djebrani et al. (2012) considered a mobile manipulator consisting of a three-wheeled OWMR and a two-link manipulator. Dinh et al. (2012) proposed a tracking control method for a three-wheeled OWMR with a SCARA type of manipulator. Oftadeh et al. (2014) constructed a four wheel steered mobile manipulator. Likewise, one of the most interesting mobile manipulators that are commercially available is the Kuka youBot. It is a mobile manipulator composed of Mecanum wheels, and a manipulator.

5 Conclusions

Omnidirectional wheels have become popular for wheeled mobile robots, because they allow a robot to drive on a straight path from a given location to another without having to rotate first. Moreover, translational movement along any desired path can be combined with a rotation, so that a robot arrives to its destination at the correct angle faster than a non-holonomic robot does. These capabilities make the robot highly maneuverable, which is very helpful in both indoor and outdoor applications, in particular, in narrow spaces and crowded environments.

Table 1 Advantages and disadvantages of different wheel types

Wheel types	Advantages	Disadvantages
Universal wheels	• Simple to control • Cost-effective setup with low space and weight requirements • Without a steering mechanism, less complex mechanical design	• Sensitive to floor irregularities • Discontinuous wheel contact • Susceptible to slippage • Low load capacity • Poor ground clearance • Complicated in odometry when two rows of the rollers are used • Perfect orientation of the wheel axis required
Mecanum wheels	• Simple to control • Cost-effective setup with low space and weight requirements • Without a steering mechanism, less complex mechanical design • Easy chassis body fabrication because the wheels are mounted inline.	• Sensitivity to floor irregularities • Discontinuous wheel contact • Susceptible to slippage • Low load capacity • Poor ground clearance • Complex wheel design • Actuation redundancy and suspension required
Powered castor wheels	• High load capacity • Robust to floor conditions • Simple concept • Simple wheels • Continuous wheel contact • High ground clearance	• High friction and scrubbing while steering • Expensive, heavy and high space required due to the additional steering mechanism • Complex mechanical design • Complex to program and control • Actuation redundancy
Steerable standard wheels	• High load capacity • Robust to floor conditions • Simple concept • Simple wheels • Continuous wheel contact • High ground clearance	• High friction and scrubbing while steering • Expensive, heavy and high space required due to the additional steering mechanism • Complex mechanical design • Complex to program and control • Actuation redundancy

This paper reviewed and analysed the existing literature concerning an OWMR equipped with universal wheels, Mecanum wheels, PCWs, and steerable standard wheels, since they have been commercially available and popularly used. To help robotic designers to choose an appropriate wheel mechanism, Table 1 presents advantages and disadvantages of each type of OWMRs. Moreover, wheelchairs and healthcare vehicles, RoboCup competitions, material transportation and cooperative manipulation were presented in this paper since they have been practical applications where omnidirectional wheels have been successfully employed.

To date, a variety of practical applications utilising omnidirectional wheels have been proposed by several research groups. However, to improve the performance and reliability of this type of robots, the accurate dynamic model is required for the real situation especially for heavy and fast moving robots or acceleration or deceleration. This problem would be an interesting research direction in the future.

References

Adascalitei, F. and Doroftei, I. (2011) 'Practical applications for mobile robots based on Mecanum wheels – a systematic survey', *Proceedings of the International Conference on Innovations, Recent Trends and Challenges in Mechatronics, Mechanical Engineering and New High-Tech Products Development*, September, Bucharest, Romania, pp.112–123.

Araujo, H., Conceicao, A., Oliveira, G. and Pitanga, J. (2011) 'Model predictive control based on LMIs applied to an omni-directional mobile robot', *Proceedings of the 18th IFAC World Congress*, September, Milano, Italy, pp.8171–8176.

Asama, H., Sato, M., Bogoni, L., Kaetsu, H., Matsumoto, A. and Endo, I. (1995) 'Development of an omni-directional mobile robot with 3 DOF decoupling drive mechanism', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Nagoya, Japan, pp.1925–1930.

Asama, H., Sato, M., Goto, N., Matsumoto, A. and Endo, I. (1996) 'Mutual transportation of cooperative mobile robots using forklift mechanisms', *Proceedings of the International Conference on Robotics and Automation*, April, Minneapolis, MN, pp.1754–1759.

Balkcom, D., Kavathekar, P. and Mason, M. (2008) 'The minimum-time trajectories for an omni-directional vehicle', in Akella, S., Amato, N., Huang, W. and Mishra, B. (Eds.): *Springer Tracts in Advanced Robotics*, Springer, Vol. 47, pp.343–358.

Ball, D., Lehnert, C. and Wyeth, G. (2010) 'A practical implementation of a continuous isotropic spherical omnidirectional drive', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Anchorage, Alaska, pp.3775–3780.

Barreto S,J., Conceicao, A., Dorea, C., Martinez, L. and De Pieri, E. (2014) 'Design and implementation of model-predictive control with friction compensation on an omnidirectional mobile robot', *IEEE/ASME Transactions on Mechatronics*, Vol. 19, No. 2, pp.467–476.

Berkemeier, M.D. and Ma, L. (2005) 'Discrete control for visual servoing the ODIS robot to parking lot lines', *Proceedings of the IEEE International Conference on Robotics and Automation*, April, Barcelona, Spain, pp.3149–3154.

Berntorp, K., Olofsson, B. and Robertsson, A. (2014) 'Path tracking with obstacle avoidance for pseudo-omnidirectional mobile robots using convex optimization', *Proceedings of the American Control Conference*, June, Portland, Oregon, USA, pp.517–524.

Betourne, A. and Campion, G. (1996) 'Dynamic modelling and control design of a class of omnidirectional mobile robots', *Proceedings of the IEEE International Conference on Robotics and Automation*, April, Minneapolis, MN, pp.2810–2815.

Borrero, G.H., Becker, M., Archila, J.F. and Bonito, R. (2012) 'Fuzzy control strategy for the adjustment of the front steering angle of a 4WSD agricultural mobile robot', *Proceedings of the Colombian Computing Congress*, October, Medellin, Colombian, pp.1–6.

Campion, G., Bastin, G., D'Andrea-Novel and B. (1996) 'Structural properties and classification of kinematic and dynamic models of wheeled mobile robots', *IEEE Transactions on Robotics and Automation*, Vol. 12, No. 1, pp.47–62.

Chen, J., Wang, J., Ouyang, S. and Yang, Y. (2014) 'Adaptive sliding mode control based on a filter for four-wheel omni-directional mobile robots', *Cybernetics and Information Technologies*, Vol. 14, No. 2, pp.140–153.

Chen, P., Mitsutake, S., Isoda, T. and Shi, T. (2002) 'Omni-directional robot and adaptive control method for off-road running', *IEEE Transactions on Robotics and Automation*, Vol. 18, No. 2, pp.251–256.

Chen, W-H., Chen, C-P., Yu, W-S., Lin, C-H. and Lin, P-C. (2012) 'Design and implementation of an omnidirectional spherical robot omnicron', *Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, July, Kaohsiung, Taiwan, pp.719–724.

Chung, W., Moon, C-B., Jung, C. and Jin, J. (2010) 'Design of the dual offset active caster wheel for holonomic omni-directional mobile robots', *International Journal of Advanced Robotic Systems*, Vol. 7, No. 4, pp.101–106.

Conceicao, A., Dorea, C. and Barreto Sb, J. (2010) 'Predictive control of an omnidirectional mobile robot with friction compensation', *Proceedings of the Latin American Robotics Symposium and Intelligent Robotics Meeting (LARS)*, October, Sao Bernardo do Campo, Brazil, pp.30–35.

Conceicao, A., Moreira, A. and Costa, P. (2006) 'Dynamic parameters identification of an omni-directional mobile robot', *Proceedings of the International Conference on Informatics in Control, Automation and Robotics*, August, Setubal, Portugal, pp.565–570.

Connette, C.P., Pott, A., Hagele, M. and Verl, A. (2010) 'Addressing input saturation and kinematic constraints of overactuated undercarriages by predictive potential fields', *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, October, Taipei, Taiwan, pp.4775–4781.

Cooney, J., Xu, W.L. and Bright, G. (2004) 'Visual dead-reckoning for motion control of a Mecanum-wheeled mobile robot', *Mechatronics*, Vol. 14, No. 6, pp.623–637.

Damoto, R., Cheng, W. and Hirose, S. (2001) 'Holonomic omni-directional vehicle with new omni-wheel mechanism', *Proceedings of the International Conference on Robotics and Automation*, May, Seoul, Korea, pp.773–778.

DaneshPanah, M., Abdollahi, A., Ostadi, H. and Samani, H.A. (2007) 'Comprehensive omni-directional soccer player robots', in Lima, P. (Ed.): *Robotic Soccer*, pp.347–374, inTech.

Dickerson, S.L. and Lapin, B.D (1991) 'Control of an omni-directional robotic vehicle with Mecanum wheels', *Proceedings of the National Telesystems Conference,* March, Atlanta, USA, pp.323–328.

Diegel, O., Badve, A., Bright, G., Potgieter, J. and Tlatle, S. (2002) 'Improved Mecanum wheel design for omni-directional robots', *Proceedings of the Australian Conference on Robotics and Automation*, November, Auckland, Australia, 117–121.

Dietrich, A., Wimbock, T., Albu-Schaffer, A. and Hirzinger, G. (2011) 'Singularity avoidance for nonholonomic, omnidirectional wheeled mobile platforms with variable footprint', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Shanghai, China, pp.6136–6142.

Dinh, V-T., Doan, P., Hung, N., Kim, H. and Kim, S. (2012) 'Tracking control of a three-wheeled omnidirectional mobile manipulator system with disturbance and friction', *Journal of Mechanical Science and Technology*, Vol. 26, No. 7, pp.2197–2211.

Djebrani, S., Benali, A. and Abdessemed, F. (2012) 'Modelling and control of an omnidirectional mobile manipulator', *International Journal of Applied Mathematics and Computer Science,* Vol. 22, No. 3, pp.601–616.

Egorova, A., Gloye, A., Goktekin, C., Liers, A., Luft, M., Rojas, R., Simon, M., Tenchio, O. and Wiesel, F. (2005) 'FU Fighters small size team 2004', Nardi, D., Riedmiller, M., Sammut, C. and Santos-Victor, J. (Eds.): *RoboCup-2004: Robot Soccer World Cup VIII*, pp.394–401.

Endo, T. and Nakamura, Y. (2005) 'An omnidirectional vehicle on a basketball', *Proceedings of the International Conference on Advanced Robotics*, July, Seattle, WA, pp.573–578.

Ferriere, L. and Raucent, B. (1998) 'ROLLMOBS, a new universal wheel concept', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Leuven, Belgium, pp.1877–1882.

Fukuda, T., Huang, J., Di, P. and Sekiyama, K. (2015) 'Motion control and fall detection of intelligent cane robot', in Mohammed, S., Moreno, J., Kong, K. and Amirat, Y. (Eds.): *Intelligent Assistive Robots*, pp.317–337, Springer International Publishing.

Ghariblu, H., Moharrami, A. and Ghalamchi, B. (2011) 'Design and prototyping of autonomous ball wheel mobile robots', in Gacovski, Z. (Ed.): *Mobile Robots – Current Trends*, pp.363–373, InTech.

Goller, M., Kerscher, T., Ziegenmeyer, M., Ronnau, A., Zollner, J.M. and Dillmann, R. (2009) 'Haptic control for the interactive behavior operated shopping trolley InBOT', *Proceedings of the New Frontiers in Human-Robot Interaction Workshop of the Convention on Artificial Intelligence and Simulation of Behaviour*, April, Edinburgh, Scotland, pp.1–6.

Heinemann, P., Haase, J. and Zell, A. (2006) 'A combined Monte-Carlo localization and tracking algorithm for RoboCup', *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, October, Beijing, China, pp.1535–1540.

Heß, D., Kunemund, F. and Rohrig, C. (2013) 'Linux based control framework for Mecanum based omnidirectional automated guided vehicles', *Proceedings of the World Congress on Engineering and Computer Science*, October, San Francisco, USA, pp.395–400.

Holmberg, R. and Khatib, O. (2000) 'Development and control of a holonomic mobile robot for mobile manipulation tasks', *International Journal of Robotics Research*, Vol. 19, No. 11, pp.1066–1074.

Hsu, P., Hsu, Y., Chang, K. and Geiser, C. (2012) 'Mobility assistance design of the intelligent robotic wheelchair', *International Journal of Advanced Robotic Systems*, Vol. 9, No. 244, pp.1–10.

Huang, H-C. and Tsai, C-C. (2008) 'FPGA implementation of an embedded robust adaptive controller for autonomous omnidirectional mobile platform', *IEEE Transactions on Industrial Electronics*, Vol. 56, No. 5, pp.1604–1616.

Hyunseok, L., Hongseok, J., Yeongmin, N. and Jongkyu, P. (2013) 'Fabrication of omni-directional driving system using unconstrained steel ball', *Proceedings of the International Conference on Fracture and Strength of Solids*, June, Jeju, Korea, pp.1–6.

Ilon, B.E. (1975) *Wheels for a Course Stable Self-propelling Vehicle Movable in Any Desired Direction on the Ground or Some Other Base*, US Patent 3,876,255.

Indiveri, G. (2009) 'Swedish wheeled omnidirectional mobile robots: kinematics analysis and control', *IEEE Transactions on Robotics*, Vol. 25, No. 1, pp.164–171.

Inoue, Y., Hirama, T. and Wada, M. (2013) 'Design of omnidirectional mobile robots with ACROBAT wheel mechanisms', *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, November, Tokyo, Japan, pp.4852–4859.

Ishigami, G., Overholt, J. and Iagnemma, K. (2012) 'Multi-material anisotropic friction wheels for omnidirectional ground vehicles', *Journal of Robotics and Mechatronics*, Vol. 24, No. 1, pp.261–267.

Ishigami, G., Pineda, E., Overholt, J., Hudas, G. and Iagnemma, K. (2011) 'Performance analysis and odometry improvement of an omnidirectional mobile robot for outdoor terrain', *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, September, San Francisco, CA, pp.4091–4096.

Jacobs, T., Hesse, M. and Verl, A. (2014) 'Evaluation of wheel mechanisms for omnidirectional robot undercarriages', *Proceedings of the International Symposium on Robotics and the German Conference on Robotics*. June, Munich, Germany, pp.190–196.

Jiang, Y., Wang, S., Ishida, K., Kobayashi, Y. and Fujie, M. (2014) 'Directional control of an omnidirectional walking support walker: adaptation to individual differences with fuzzy learning', *Advanced Robotics*, Vol. 28, No. 7, pp.479–485.

Jung, E-J., Chung, J., Lee, J., Yi, B. and Kim, W. (2007) 'Implementation of an embedded omni-directional mobile robot with active caster wheels', *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, October, San Diego, CA, pp.3911–3918.

Jung, M. and Kim, J. (2001) 'Fault tolerant control strategy for OmniKity-III', Proceeding of the *IEEE International Conference on Robotics Automation*, May, Seoul, Korea, pp.3370–3375.

Kalman, V. (2013) 'Omnidirectional wheel simulation – a practical approach', *Acta Technica Jaurinensis*, Vol. 6, No. 2, pp.73–90.

Kalmar-Nagy, T., D'Andrea, R. and Ganguly, P. (2004) 'Near-optimal dynamic trajectory generation and control of an omnidirectional vehicle', *Robotics and Autonomous Systems*, Vol. 46, No. 1, pp.47–64.

Kanjanawanishkul, K. and Zell, A. (2009) 'Path following for an omnidirectional mobile robot based on model predictive control', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Kobe, Japan, pp.3341–3346.

Kasaei, S., Kasaei, S. and Kasaei, S. (2010) 'Design and implementation solenoid based kicking mechanism for soccer robot applied in Robocup-MSL', *International Journal of Advanced Robotic Systems*, Vol. 7, No. 4, pp.73–80.

Killpack, M., Deyle, T., Anderson, C. and Kemp, C. (2010) 'Visual odometry and control for an omnidirectional mobile robot with a downward-facing camera', *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, October, Taipei, Taiwan, pp.139–146.

Kim, D., Wook, H. and Hong, S. (2003) 'Geometric kinematics and applications of a mobile robot', *International Journal of Control, Automation, and Systems*, Vol. 1, No. 3, pp.376–384.

Kim, J., Park, J. and Kim, S. (2012) 'Inertial navigation system for omni-directional AGV with Mecanum wheel', *Advances in Mechanical Engineering*, Vol. 2, No. 1, pp.48–54.

Koestler, A. and Braunl, T. (2004) 'Mobile robot simulation with realistic error models', *Proceedings of the International Conference on Autonomous Robots and Agents*, December, Palmerston North, New Zealand, pp.46–51.

Kumaga, M. and Ochiai, T. (2009) 'Development of a robot balanced on a ball – application of passive motion to transport', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Kobe, Japan, pp.4106–4111.

Lam, T.L., Qian, H., Xu, Y. and Xu, G. (2009) 'Omni-directional steer-by-wire interface for four wheel independent steering vehicle', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Kobe, Japan, pp.1383–1388.

Lauria, M., Nadeau, I., Lepage, P., Morin, Y., Giguere, P., Gagnon, F., Letourneau, D. and Michaud, F. (2006) 'Design and control of a four steered wheeled mobile robot', *Proceedings of the Annual Conference of IEEE Industrial Electronics*, November, Paris, France, pp.4020–4025.

Lee, J.H., Kim, B.K., Tanikawa, T. and Ohba, K. (2007) 'Kinematic analysis on omni-directional mobile robot with double-wheel-type active casters', *Proceedings of the International Conference on Control, Automation and Systems*, October, Seoul, Korea, pp.1217–1221.

Leng, C., Cao, Q. and Huang, Y. (2008) 'A motion planning method for omnidirectional mobile robot based on the anisotropic characteristics', *International Journal of Advanced Robotic Systems*, Vol. 5, No. 4, pp.327–340.

Li, T.S., Chen, C-Y., Hung, H-L. and Yeh, Y-C. (2008) 'A fully fuzzy trajectory tracking control design for surveillance and security robots'*, Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, October, Singapore, pp.1995–2000.

Li, Y., Oetomo, D., Ang Jr., M. and Lim, C. (2005) 'Torque distribution and slip minimization in an omnidirectional mobile base', *Proceedings of the International Conference on Advanced Robotics*, July, Seattle, WA, pp.567–572.

Liu, Y., Zhu, J., Williams II, R. and Wu, J. (2008) 'Omni-directional mobile robot controller based on trajectory linearization', *Robotics and Autonomous Systems*, Vol. 56, No. 5, pp.461–479.

Loh, W.K., Low, K.H. and Leow, Y.P. (2003) 'Mechatronics design and kinematic modelling of a singularityless omni-directional wheeled mobile robot', *Proceedings of the IEEE International Conference on Robotics and Automation*, September, Taipei, Taiwan, pp.3237–3242.

Lupian, L. and Rabadan-Martin, J. (2009) 'Segment-wise optimal trajectory execution control for four-wheeled omnidirectional mobile robots', *Proceedings of the Latin American Robotics Symposium (LARS)*, October, Valparaiso, Chile, pp.1–6.

Ma, S., Ren, C. and Ye, C. (2012) 'An omnidirectional mobile robot: concept and analysis', *Proceedings of the IEEE international Conference on Robotics and Biomimetics*, December, Guangzhou, China, pp.920–925.

Moore, K. and Flann, N. (2000) 'A six-wheeled omnidirectional autonomous mobile robot', *IEEE Control Systems Magazine*, Vol. 20, No. 6, pp.53–66.

Mori, Y., Nakano, E., Takahashi, T. and Takayama, K. (1999) 'Mechanism and running modes of new omni-directional vehicle ODV9', *Transaction of the Japan Society of Mechanical Engineers, Series C, Mechanical System, Machine Elements and Manufacturing*, Vol. 42, No. 1, pp.210–217.

Mourioux, G., Novales, C., Poisson, G. and Vieyres, P. (2006) 'Omni-directional robot with spherical orthogonal wheels: concepts and analyses', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Orlando, Florida, pp.3374–3379.

Muir, P. and Neuman, C. (1986) *Kinematic Modeling of Wheeled Mobile Robots*, Technical Report CMU-RI-TR-86-12, The Robotics Institute, Carnegie-Mellon University, Pittsburgh, PA, June.

Muir, P. and Neuman, C. (1987) 'Kinematic modeling for feedback control of an omnidirectional wheeled mobile robot', *Proceedings of the IEEE International Conference on Robotics and Automation*, March, North Carolina, pp.772–1778.

Nagarajan, U., Kantor, G. and Hollis, R. (2014) 'The Ballbot: an omnidirectional balancing mobile robot', *International Journal of Robotics Research*, Vol. 33, No. 6, pp.917–930.

Nagatani, K., Tachibana, S., Sofue, M. and Tanaka, Y. (2000) 'Improvement of odometry for omnidirectional vehicle using optical flow information', *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, November, Takamatsu, Japan, pp.468–473.

Oftadeh, R, Aref, M., Ghabcheloo, R. and Mattila, J. (2014) 'System integration for real-time mobile manipulation', *International Journal of Advanced Robotic Systems*, Vol. 11, No. 51, pp.1–9.

Pai, N-S., Hsieh, H-H. and Lai, Y-C. (2012) 'Implementation of obstacle-avoidance control for an autonomous omni-directional mobile robot based on extension theory', *Sensors*, Vol.12, No. 10, pp.13947–13963.

Parmar, J. and Savant, C. (2014) 'Selection of wheels in robotics', *International Journal of Scientific and Engineering Research*, Vol. 5, No. 10, pp.339–343.

Pin, F. and Killough, S. (1999) 'A new family of omnidirectional and holonomic wheeled platforms for mobile robot', *IEEE Transaction on Robotics and Automation*, Vol. 15, No. 6, pp.978–989.

Purwin, O. and D'Andrea, R. (2006) 'Trajectory generation and control for four wheeled omnidirectional vehicles', *Robotics and Autonomous Systems*, Vol. 54, No. 1, pp.13–22.

Qi, T., Li, C., Kai, W. and Yan, L. (2009) 'Research on motion control of mobile robot with fuzzy PID arithmetic', *Proceedings of the International Conference on Electronic Measurement and Instruments*, August, Beijing, China, pp.363–366.

Ramirez-Serrano, A. and Kuzyk, R. (2010) 'Modified Mecanum wheels for traversing rough terrain', *Proceedings of the International Conference on Autonomic and Autonomous Systems*, March, Cancun Mexico, pp.97–103.

Ransom, S., Kromer, O. and Luckemeieri, M. (2008) 'Planetary rovers with Mecanum wheels, *Proceedings of the ESA Workshop on Advanced Space Technologies for Robotics and Automation*, April, Noordwijk, The Netherlands.

Rojas, R. and Forster, A. (2006) 'Holonomic control of a robot with an omnidirectional drive', *Kunstliche Intelligenz*, Vol. 20, No. 2, pp.12–17.

Schulze, L., Behling, S. and Buhrs, S. (2011) 'Development of a micro drive-under tractor – research and application', *Proceedings of the International MultiConference of Engineers and Computer Scientists*, March, Hong-Kong, pp.823–827.

Selekwa, M.F. and Nistler, J.R. (2011) 'Path tracking control of four wheels independently steered ground robotic vehicles', *Proceedings of the IEEE Conference on Decision and Control and European Control Conference*, December, Orlando, Florida, pp.6355–6360.

Shing, C-C., Hsu, P-L. and Yeh, S-S. (2006) 'T-S fuzzy path controller design for the omnidirectional mobile robot', *Proceedings of the Annual Conference on IEEE Industrial Electronics Society*, November, Taipei, Taiwan, pp.4142–4147.

Song, J-B. and Byun, K-S. (2006) 'Design and control of an omnidirectional mobile robot with steerable omnidirectional wheels', in Buchli, J. (Ed.): *Mobile Robots, Moving Intelligence*, pp.223–240, InTech.

Stonier, D., Cho, S-H., Choi, S-L., Kuppuswamy, N. and Kim, J-H. (2007) 'Nonlinear slip dynamics for an omniwheel mobile robot platform', *Proceedings of the IEEE International Conference on Robotics and Automation*, April, Roma, Italy, pp.2367–2372.

Tadakuma, K., Hirose, S. and Tadakuma, R. (2004) 'Development of VmaxCarrier2: omni-directional mobile robot with function of step-climbing', *Proceedings of the IEEE international Conference on Robotics and Automation*, April, New Orleans, LA, pp.3111–3118.

Tadakuma, K., Tadakuma, R. and Berengeres, J. (2007) 'Development of holonomic omnidirectional vehicle with "Omni-Ball": spherical wheels', *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, October, San Diego, CA, USA, pp.33–39.

Tadakuma, K., Tadakuma, R., Kinoshita, H., Nagatani, K., Yoshida, K., Udengaard, M. and Iagnemma, K. (2008) 'Mechanical design of cylindrical track for sideways motion', *Proceedings of the IEEE International Conference on Mechatronics and Automaton*, August, Takamatsu, Japan, pp.161–167.

Tan, R., Wang, S. and Jiang, Y. (2012) 'Motion control of a cushion robot considering load change and center of gravity shift', *Journal of System Design and Dynamics*, Vol. 6, No. 5, pp.740–753.

Tavakoli, M. and Viegas, C. (2014) 'Analysis and application of dual-row omnidirectional wheels for climbing robots', *Mechatronics*, Vol. 24, No. 5, pp.436–448.

Thuilot, B., d'Andrea-Novel, B. and Micaelli, A. (1996) 'Modeling and feedback control of mobile robots equipped with several steering wheels', *IEEE Transactions on Robotics and Automation*, Vol. 12, No. 3, pp.375–390.

Timothy, A., Teatro, J., Eklund, M. and Milman, R. (2014) 'Nonlinear model predictive control for omnidirectional robot motion planning and tracking with avoidance of moving obstacles', *Canadian Journal of Electrical and Computer Engineering*, Vol. 37, No. 3, pp.151–156.

Tlale, N. and Villiers, M. (2008) 'Kinematics and dynamics modelling of a Mecanum wheeled mobile platform', *Proceedings of the International Conference on Mechatronics and Machine Vision in Practice*, December, Auckland, New Zealand, pp.657–662.

Udengaard, M. and Iagnemma, K. (2009) 'Analysis, design, and control of an omnidirectional mobile robot in rough terrain', *Journal of Mechanical Design*, Vol. 131, No. 12, pp.1–11.

Ushimia, N. and Aoba, Y. (2012) 'Development of a two-wheels caster type of odometer with a dual shaft for omnidirectional mobile robots', *Procedia Engineering*, Vol. 41, pp.163–169.

Velasco-Villa, M., Rodriguez-Cortes, H., Estrada-Sanchez, I., Sira-Ramirez H. and Vazquez, J.A. (2010) 'Dynamic trajectory-tracking control of an omnidirectional mobile robot based on a passive approach', in Hall, E. (Ed.): *Advances in Robot Manipulators*, pp.299–314, InTech.

Vrunda, A., Ravi, N. and Rohit, H. (2010) 'Design and analysis of a spherical mobile robot', *Mechanism and Machine Theory*, Vol. 45, No. 2, pp.130–136.

Wada, M. (2006) 'Virtual link model for redundantly actuated holonomic omnidirectional mobile robots', *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Orlando, Florida, pp.3201–3207.

Wada, M. (2007) 'A 4WD omnidirectional mobile platform and its application to wheelchairs', in Zhang, H. (Ed.): *Climbing and Walking Robots: towards New Applications*, pp.313–334, InTech.

Wada, M. and Asada, H. (1999) 'Design and control of a variable footpoint mechanism for holonomic omnidirectional vehicles and its application to wheelchairs', *IEEE Transactions on Robotics and Automation*, Vol. 15, No. 6, pp.978–989.

Wada, M., Takagi, A. and Mori, S. (2000) 'Caster drive mechanism for holonomic and omnidirectional mobile platforms with no over-constraint', *Proceedings of the IEEE International Conference on Robotics and Automation*, April, San Francisco, CA, pp.1531–1538.

Watanabe, K. (1998) 'Control of an omnidirectional mobile robot', *Proceedings of the International Conference on Knowledge-Based Intelligent Electronic Systems*, April, Adelaide, Australia, pp.51–60.

Weitzenfeld, A., Biswas, J., Akar, M. and Sukvichai, K. (2014) 'RoboCup small-size league: past, present and future', *Proceedings of the RoboCup Symposium*, July, Joao Pessoa, Brazil.

West, A. and Asada, H. (1997) 'Design of ball wheel mechanisms for omnidirectional vehicles with full mobility and invariant kinematics', *ASME Journal of Mechanical Design*, Vol. 119, No. 2, pp.153–161.

Williams II, R. and Wu, J. (2010) 'Dynamic obstacle avoidance for an omnidirectional mobile robot', *Journal of Robotics*, Article ID 901365, pp.1–14.

Wilson, L., Williams, C., Yance, J., Lew, J. and Williams II., R. (2001) 'Design and modeling of a redundant omnidirectional RoboCup goalie', *Proceedings of the 2001 RoboCup International Symposium*, August, Seattle, WA, pp.1–10.

Wong, C-C., Lin, Y-H., Lee, S-A. and Tsai, C-H. (2005) 'GA-based fuzzy system design in FPGA for an omni-directional mobile robot', *Journal of Intelligent and Robotic Systems*, Vol. 44, No. 4, pp.327–347.

Yamada, T., Watanabe, K., Kiguchi, K. and Izumi, K. (2001) 'Dynamic model and control for a holonomic omnidirectional mobile robot', *Journal of Autonomous Robots*, Vol. 11, No. 2, pp.173–189.

Yamashita, A., Asama, H., Kaetsu, H., Endo, I. and Arai, T. (2001) 'Development of a step-climbing omni-directional mobile robot', *Proceedings of the International Conference on Field and Service Robotics*, July, Helsinski, Finland, pp.327–332.

Yang, H., Borenstein, J. and Wehe, D. (2000) 'Sonar-based obstacle avoidance for a large, non-point, omni-directional mobile robot', *Proceedings of the Spectrum International Conference on Nuclear and Hazardous Waste Management*, September, Chattanooga, TN, pp.24–28.

Yavin, Y. (2003) 'Modelling the motion of a car with four steerable wheels', *Mathematical and Computer Modelling*, Vol. 38, No. 10, pp.1029–1036.

Yu, H., Spenko, M. and Dubowsky, S. (2004) 'Omni-directional mobility using active split offset castors', *Journal of Mechanical Design*, Vol. 126, No. 5, pp.822–829.

Zhang, D., Li, Z. and Chen, J. (2012) 'Design and optimization of an omnidirectional permanent-magnetic wheeled wall-climbing microrobot with MEMS-based electromagnetic micromotors', *Advanced Robotics*, Vol. 26, Nos. 1–2, pp.197–218.

Zhao, D., Deng, X. and Yi, J. (2009) 'Motion and internal force control for omnidirectional wheeled mobile robots', *IEEE/ASME Transactions on Mechatronics*, Vol. 14, No. 3, pp.382–387.

Zou, J-T. (2011) 'The development of the omnidirectional mobile home care robot', in Gacovski, Z. (Ed.): *Mobile Robots – Current Trends*, pp.345–362.