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Holonomic and Omnidirectional Locomotion Systems for Wheeled Mobile Robots: A Review

M. Juhairi Aziz Safar*

School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, Arau, Perlis, Malaysia

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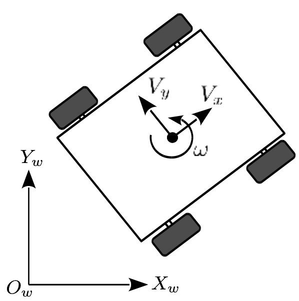
*Corresponding author
juhairi@unimap.edu.my

Graphical abstract



Abstract

Holonomic and omnidirectional locomotion systems are best known for their capability to maneuver at any arbitrary direction regardless of their current position and orientation with a three degrees of freedom mobility. This paper summarizes the advancement of holonomic and omnidirectional locomotion systems for wheeled mobile robot applications and discuss the issues and challenges for future improvement.

Keywords: Omnidirectional, holonomic, mobile robot, locomotion

Abstrak

Sistem gerakalih holonomik dan semua arah amat dikenali disebabkan kebolehannya untuk diolahgerak pada sebarang arah tanpa perlu mengambil kira kedudukan dan orientasi semasa dengan mobility tiga darjah kebebasan. Kertas kerja ini meringkaskan perkembangan sistem gerakalih holonomic dan semua arah untuk aplikasi robot mudah alih dan membincangkan isu-isu serta cabaran-cabaran untuk penambahbaikan pada masa hadapan.

Kata kunci: Semua arah, holonomik, robot mudah alih, gerakalih

1.0 INTRODUCTION

Wheeled mobile robots are widely used in various fields including industry, agriculture, military, domestic and medical supports. Most of them usually designed to operate in semi or fully-autonomous mode in very constrained spaces. In addition to the autonomy, there are another three essential aspects to be considered for designing these kind of wheeled mobile robots which include the mobility, control and positioning. The mobility of wheeled mobile robots indicates the capability of the mobile robots to perform motion and usually associated with the number of degrees of freedom (DOF). It is desirable for any mobile robot to have a full control of 3-DOFs motion which described the capability for lateral, longitudinal and rotational motion. Thus, it is possible to enable a mobile robot to move at any desired direction even in a very constrained space. There are various approaches available that offer omndirectional ability to mobile robots especially using specialized wheels such as mecanum [1], orthogonal [2] and ball wheels [3]. There are also a few approaches using the standard wheels such introduced in [4], [5]. However, not all omnidirectional platforms were holonomic [5], [6]. This paper summarizes various approaches of holonomic and omnidirectional locomotion system for both specialized and standard wheel structures. The continuous progress of innovation on each approach is presented and discussed for further improvement in future.

2.0 OMDIRECTIONAL LOCOMOTION SYSTEM

A mobile robot on any horizontal plane can be represented by three independent values as $\boldsymbol{x} = [x \quad y \quad \phi]^T$. The value of xy and ϕ represent the position and the orientation of the mobile robot in a global coordinate system, respectively. A standard differential drive system as shown in Figure 1 (left) is driven by the differences of the wheel's angular velocity and only capable to drive a forward motion by inducing V_x. No lateral velocity to the sideway of the wheels can be produced. A mobile robot with this structure needs to rotate at its center before pursuing to the desirable direction. On the other hand, a four-wheeled omnidirectional drive as shown in Figure 1 (right) can move to any desired direction instantaneously regardless of its position and orientation. It can produces linear velocity of V_x and V_y, and angular velocity of $\dot{\phi}$ at the same time. Due to these, an omnidirectional drive is able to control all the three values of x, y and ϕ, and obtained a 3-DOFs mobility. Although the differential drive at a glance can move to any direction, this structure is not an omnidirectional system since the prior rotation is necessary. The later omnidirectional drive is an example of many existing omnidirectional locomotion system.

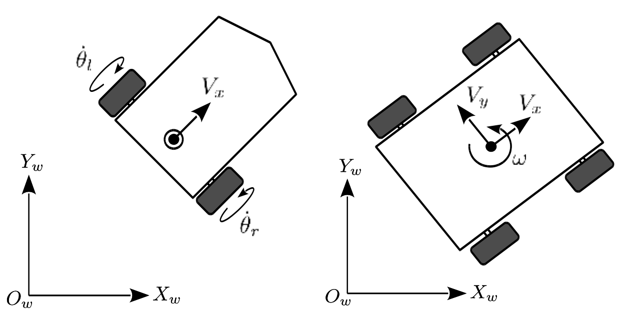


Figure 1 Differential drive (left) and omnidirectional locomotion system (right)

3.0 HOLONOMIC AND NONHOLONOMIC SYSTEMS

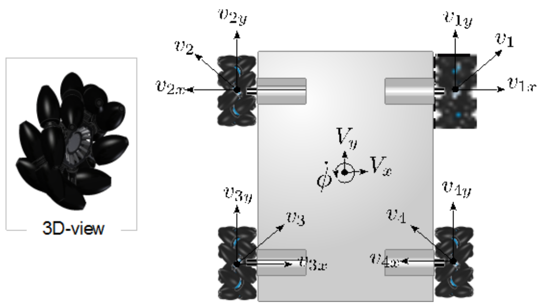
The omnidirectional locomotion system can be classified into holonomic or nonholonomic systems. In general, a holonomic mobile robot is described as a mobile robot without any kinematic constraints. The holonomic mobile robots capable to move at any arbitrary direction with 3-DOFs capability without any kinematical restriction. Conversely, the nonholonomic mobile robots may have one or more kinematic constraints. This classification can be related to the number of degree of mobility, δ_m and DOF. The mobile robot is considered as holonomic if and only if $\delta_m = \text{DOF}$. If δ_m is lesser than DOF, the mobile robot is considered as a nonholonomic system. The value of δ_m is defined as $\delta_m = 3 - \delta_s$, where δ_s is the degree of steerability which corresponds to the number of independently steerable wheels. Although the omnidirectional mobile robots are always referred to holonomy, there are still some omnidirectional platforms were actually nonholonomic. These kind of platforms which also named as pseudo-omnidirectional [5], [6] requires preliminary maneuvering for reorientation of steering wheel which may affect the time-travel cost and the spaces needed. The orientation of the orientable wheels in these platforms always need to be aligned with the desirable moving direction. Due to these drawbacks, the nonholonomic omnidirectional platforms were less desirable in comparison with holonomic omnidirectional platforms.

4.0 HOLONOMIC AND OMNIDIRECTIONAL MOBILE ROBOTS

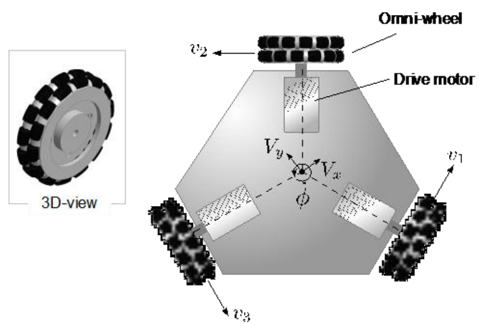
A major achievement for mobile robots is to obtain both holonomy and omnidirectional capabilities. In this section we describe a variety of holonomic and omnidirectional mechanisms for wheeled mobile robots based on the existing applications. It can be classified into several groups: mecanum wheels, universal wheels, orthogonal wheels, crawler mechanisms, spherical or ball wheels, synchro-drive mechanism and active-caster drives.

4.1 Mecanum/ Swedish Wheels and Omniwheels

The first mecanum wheel [7] is introduced in year 1975 for an omnidirectional vehicle [1]. This wheel which also known as Swedish wheel has very unique structure where several passive rollers are arranged at certain angle along the outer rim of the wheel as shown in Figure 2. A driving velocity of the wheel induces a lateral direction force, v_i at the rollers. This v_i produces driving forces in the lateral and longitudinal direction of the wheel itself. By setting the roller angle as θ_i, the resolved forces in $xy-$axes can be calculated as $v_{ix} = \cos\theta_i$ and $v_{iy} = \sin\theta_i$. Thus, controlling the velocity and the direction of the wheels rotation produce a 3-DOFs motion at the center of the vehicle. A standard omnidirectional vehicle with 45 degree roller mecanum wheels requires four units of mecanum wheel and arranged as shown in Figure 2. Another configuration with 90 degree roller wheels, which also known as omniwheel [8] or universal wheel, has eliminates the lateral direction forces due to the non-existing nonholonomic constraint. Thus, omniwheel produces almost the same traction as the standard wheel but induce a pure rolling at the lateral direction. At least three units of independent omniwheel is required to produce the 3-DOFs mobility. Typical structures with three and four-wheeled omniwheel robots are shown in Figure 2. An innovative approach by converting the passive rollers in the omniwheel into active rollers reduces the necessary number of wheels. Using only

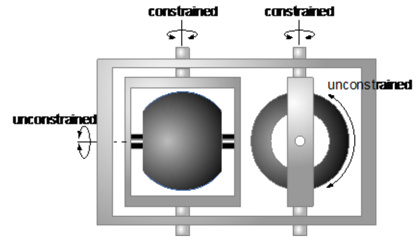


(a) Omnidirectional mobile robot with mecanum wheels as proposed in [7]

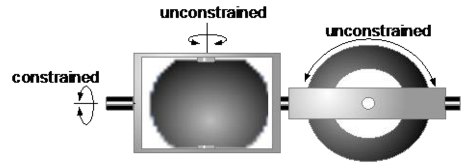


(b) Omnidirectional mobile robot with omniwheels as proposed in [8]

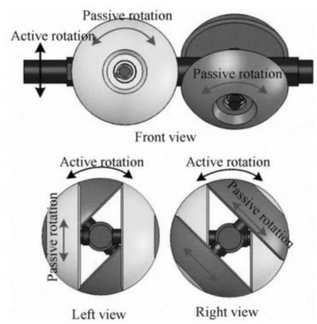
Figure 2 Mecanum wheel and Omniwheel

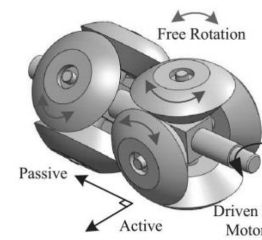


(a) Lateral assembly [2]



(b) Longitudinal assembly [2]





(c) My-Wheel [13] (d) My-Wheel II [14]

Figure 3 Orthogonal wheels

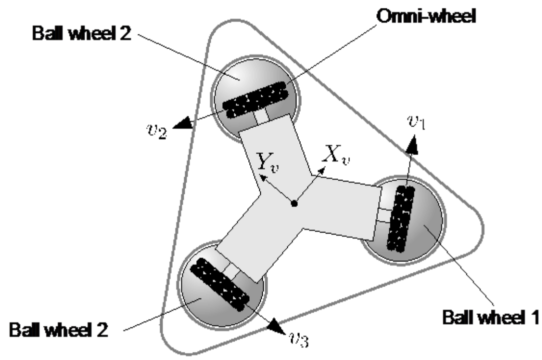
one active omniwheel can produce the same 3-DOFs mobility [9].

4.2 Orthogonal Wheels

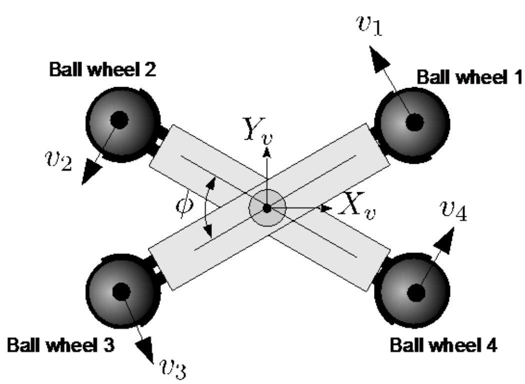
A novel locomotion system as shown in Figure 3 using a pair of sliced spherical wheels has been presented by Pin and Killough [2]. This pair of sliced spherical wheel is placed at the driving axle in an orthogonal configuration. The orthogonal wheels provides a normal traction in a given direction while produce a pure free rolling in the other perpendicular direction. One unit of orthogonal wheel assembly comprises of two units sliced wheel which arranged at 90 degree angle. Due to this, the contact with the ground can be assured. Two layouts of orthogonal wheels are presented: longitudinal assembly and lateral assembly. Holonomic and omnidirectional capability is achieved using three pairs of those assemblies with the same architecture as the three-wheeled omniwheel vehicle. The concepts and kinematics model for both assemblies are presented in [10]. While, the dynamical model and control methods for omnidirectional mobile robots with orthogonal wheels are presented in [11], [12]. An improvement to this structure has been proposed by increasing the contact area through an assembly comprises of several crown slices to form a ball. [13], [14] Each crown slices can rotate freely around its center. These approaches offer better payload compared to the former orthogonal wheel but still insensitive to fragments and irregularities on the floor.

4.3 Spherical and Ball Wheels

West *et al*. [3] and Ferriere [15] presented a three ball wheels of omnidirectional mobile robot. West *et al.* used ring bearing and rollers to control the rotation and translation of the ball wheels. Ferriere replaced the bearing which used for controlling the rotation of the ball wheel by applying omni-wheel to each of the ball wheel as shown in Figure 4(a). Similar layouts also are presented by Ghariblu [16] and Ishida [17]. Mascaro *et al.* introduced a four-wheeled structure of ball wheel mechanism for wheelchair and bed system [18]. Instead of a fix footprint, Wada *et al.* [19] introduced an improvement to the design of Mascaro *et al.* by applying a re-configurable footprint mechanism as shown in Figure 4(b). The shape of the footprint will change depending on the space of maneuver. In a small space, the robot able to change the width of the robot to adapt with the surroundings. The manipulation of ball in each ball wheel unit is similar to the design of West and Asada. Recently, Ok *et al.* [20] introduced a link-driven spherical mechanism in two layouts named SO(2) and SO(3). Another interesting mechanism named omni-ball by Tadakuma *et al.* [21] solved the discontinuous ground contact point problem in the conventional omni-wheel design. Statically unstable

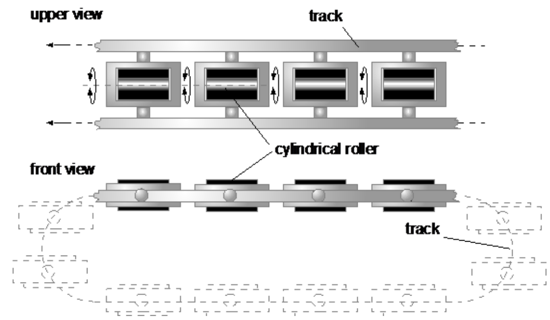


(a) Ball wheel mechanism with omniwheels [15]

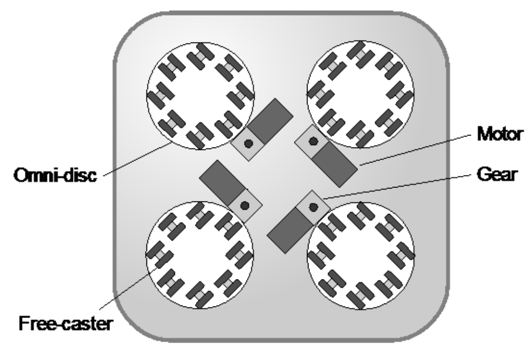


(b) Ball wheel with reconfigurable footprint [19]

Figure 4 Example of spherical and ball wheel mechanisms



(a) Vuton crawler mechanism [25]



(b) Vuton II [26]

Figure 5 Crawler mechanisms of Vuton family

layout of a single spherical wheel mechanism is presented by Nagarajan *et al.* [22]. A dynamical control is essential to keep the mobile robot stable during maneuver. A different approach by Chen *et al*. [23] uses an inner driving mechanism to generate a rolling power for a spherical robot.

4.4 Crawler Mechanisms

Nishikawa *et al.* [24] presented a holonomic omnidirectional mobile robot using a crawler mechanism constructed by spherical balls. The vehicle comprises of two parallel tracks at the side which hold the spherical balls. The spherical balls are arranged into a circulating chain that controls forward and backward movement. At the same time, the spherical balls hold the load from the body through two controlled parallel rods. By rotating the rods the mobile platform can be moved in the desired sideways direction. Combining both mechanisms enabled an omnidirectional motion. However, this mechanism has significant sideways slippage and loss of contact with the ground especially during turns or uneven ground.

Hirose and Amano [25] developed an improved version of this crawler named Vuton by replacing the spherical wheel with cylindrical free rollers as shown in Figure 5(a). This crawler has four units of track with wider contact surface to the ground. It has eliminated the sideways slippage and able to work with high payload. Another version of Vuton named Vuton II has been developed later by Damoto *et al.* [26] as shown in Figure 5(b) using the four sets of active Omni-disc. Each Omni-disc comprised of several casters and gears. This new vehicle is designed to be lower in cost and shorter in stature than the Vuton-I, but still maintains a reasonably high payload capacity.

4.5 Synchro-drive Mechanism

Wada *et al.* [27] introduced a synchro-drive caster mechanism as shown in Figure 6. Wheel sprockets of all drive-casters are mechanically coupled by a drive belt and simultaneously driven by a wheel motor. Steering sprockets are coupled by another drive belt as well and driven by a steering motor. Since all drive-casters are driven and steered by common two actuators, each wheel executes the same motions at all times. Then each wheel gives an equal and parallel velocity vector to the drive unit, a resultant velocity vector of the drive unit would be identical to the wheel velocity vector. Another motor is added to the rotational stage to control the rotation of a vehicle frame relating to the drive unit to produce a holonomic motion.

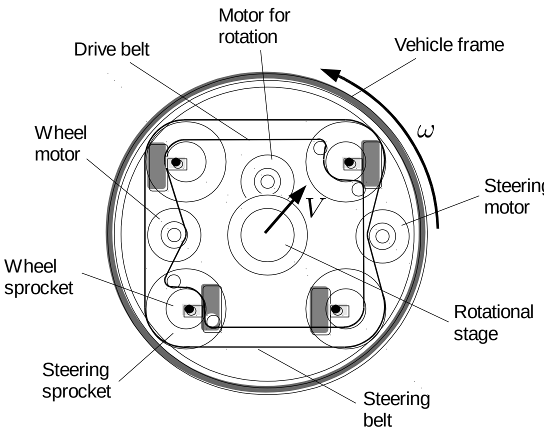
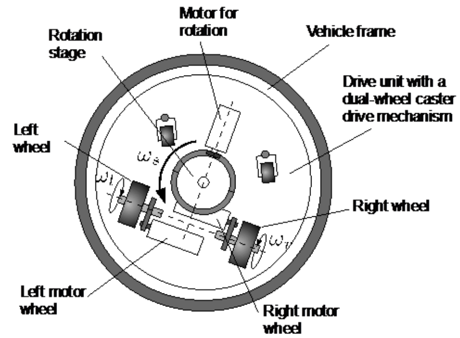


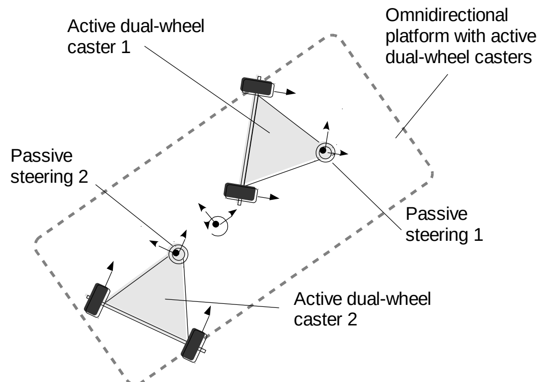
Figure 6 Synchro-drive caster mechanism [27]

4.5 Active Casters

Wada and Mori [28], [29] developed a holonomic and omnidirectional mobile robot using two steered driving wheels, in which the wheel has the offset distance between the axle and steering axis like a caster and can use a normal tire such as a rubber tire and a pneumatic tire, instead of a specialized wheel mechanism as shown in Figure 7(a). An active dual-wheel caster assembly was suggested by Han *et al.* [30], in which a wheeled mechanism has a passive steering axis with offset arranged on the front of a conventional two independent driving wheels mechanism, and a holonomic and omnidirectional mobile robot was realized by using two or more of these assemblies (Figure 7(b)). This assembly can generate two-degrees of freedom velocity on the passive steering axis, because of the difference between the angular velocities of the left and right wheels. In addition, it can of course use a normal tire and is simple in structure. Another similar mechanism to Han *et al.* is proposed by Yu *et al.* [31] in the name of Active Split Caster Offset (ASOC). The improved version of this mechanism for uneven and rough terrain by exploiting the suspension and its control system is mentioned in [4]. Four units of ASOC are applied for better stability on rough terrain. Wada [32] introduced the mechanism and control of a 4WD holonomic and omnidirectional wheelchairs. The mechanism consists of two standard differential drive mechanisms in rear position and another two omni-wheels at the front. Both omni-wheels at the front are connected with the belt to the respected actuator for the rear differential drive. The concept is similar to the offset driving caster principle as explained above. The front omni-wheels produced an additional traction force while at the same time allowing the movement in the lateral direction.



(a) Offset driving caster by Wada *et al.* [28]



(b) Omnidirectional robot with two offset driving casters [30]

Figure 7 Active casters and offset driving mechanism

5.0 SUMMARY

Table 1 shows the comparison between all reviewed holonomic and omnidirectional locomotion systems. Most of the existing locomotion system for holonomic and omnidirectional drive were constructed using specialized wheels except for synchro-drive and offset steering of active casters. Almost all specialized wheels are too complicated, thus require a lot of expertise for designing and assembling the structures. The misalignment in special wheels could probably worsen the slippage and error which already exist in most wheeled mobile robots. Although the complexity using the standard wheels are lower than the specialized wheels, it still required proper arrangement especially for synchro-drive to make sure the transmission to all wheels is equal and be synchronized. Meanwhile in offset-steering and active casters especially in [29], [30], proper wiring system to connect the actuator through the steering units without constrained the steerable angle is necessary.

Table 1 Comparison of various holonomic and omnidirectional locomotion systems

Group	Wheel Type	Complexity	Traction	Vibration	Footprint
Mecanum/ Swedish wheels and omniwheels [1], [7]–[9]	Special	High	Low	Yes	Fix
Orthogonal wheels [2], [10]–[14]	Special	High	Low	Yes	Fix
Spherical and ball wheels [15]–[17], [20]–[23], [34]	Special	High	High	No	Fix, Small
Crawlers mechanism [25], [26]	Special	High	High	No	Fix
Synchro-drive mechanism [27]	Standard	High	High	No	Almost uniform
Active casters and offset-steering [28], [30]–[32], [35]	Standard	Low	High	No	Fix/ Variable

Another approach by gearing transmission also introduced in [33] to avoid those wiring requirement. The major design problem for all these locomotion systems are the lower capability to overcomes step and uneven floors.

Although the standard wheels were adapted in some locomotion systems, the size of the wheel is constrained and only consider for indoor applications. Overcoming steps is one of the existing problem for this locomotion system. While, in term of traction, the structure with the conventional wheels are more superior to the specialized wheels. The contact to the ground in most special wheels is discontinuous due to the gap between the rollers. This design problem affects the performance of traction in those locomotion systems. Researchers introduced an innovation to address this problems [13], [14].

In addition, the existing gaps also produced an annoying vibrations to the overall structures and exposed to dirt which require a frequent maintenance. In most locomotion systems, the static stability is ensured due to the fix footprint and unchanged support polygon. In mechanism such as [22], the contact point is too limited, thus the unstable condition need to be overcome using dynamic stability control. The structure of offset-steering such introduced in [30] is unstable due to the rapid changes in the footprints. This problem can be overcome by mounting passive casters to increase the static stability [31] or by implementing a proper tip-over prevention techniques [36].

6.0 CONCLUSION

Based on the review, it can be seen that the holonomic and omnidirectional locomotion can be realized by many existing mechanisms and still open for further exploration although the current trend leads to the innovation of the existing groups. Every mechanisms have their own specialty and drawbacks due to the specific design problems. Further innovation of the design especially to facilitate for outdoor applications also desirable to support the wheeled mobile robots as well as the developing personal mobility technologies.

References

[1] Ilon, B. E. 1975. *Wheels for a Course Stable Selfpropelling Vehicle Movable in Any Desired Direction on the Ground or Some Other Base*. United States. 3876255.

[2] Pin, F. G., Killough, S. M. 1994. A New Family of Omnidirectional and Holonomic Wheeled Platforms for Mobile Robots. *IEEE Trans Robot Autom*. 10(4): 480-488.

[3] West, M., Asada, H. 1995. Design and Control of Ball Wheel Omnidirectional Vehicles. *Proc. 1995 IEEE Int. Conf Robot Autom.* 1931-1939.

[4] Udengaard, M., Iagnemma, K. 2009. Analysis, Design, and Control Of An Omnidirectional Mobile Robot In Rough Terrain. *ASME J Mech Des*. 131(12): 121002 (1-11).

[5] Clavien, L., Fr, J. 2010. Teleoperation of AZIMUT-3, an Omnidirectional Non-Holonomic Platform with Steerable Wheels. *IEEE Trans Robot*. 2515-2520.

[6] Hashimoto, M., Suizu, N., Fujiwara, I., Oba, F. 1999. Path Tracking Control of a Non-Holonomic Modular Omnidirectional Vehicle. *Proc. IEEE Int. Conf. on Systems. Man, and Cybernetics*. 637-642.

[7] Han, K., Choi, O., Kim J., Kim, H., Lee, J. S. 2009. Design and Control of Mobile Robot with Mecanum Wheel. *Proc of ICROS-SICE Int Joint Conf*. 2932-2938.

[8] Indiveri, G. 2009. Swedish Wheeled Omnidirectional Mobile Robots: Kinematics Analysis and Control. *IEEE Trans Robot*. 25(1): 164-171.

[9] Honda Motors Co. Ltd. UNI-CUB (in Japanese). http://www.honda.co.jp/UNI-CUB/.

[10] Mourioux, G., Novales, C., Poisson, G., Vieyres, P. 2006. Omni-directional Robot with Spherical Orthogonal Wheels: Concepts and Analyses. *Proc 2006 IEEE Int Conf Robot Autom.* 2: 3374-3379.

[11] Watanabe, K. 1998. Control of an Mnidirectional Mobile Robot. *Rev Lit Arts Am*. 21-23.

[12] Tang, J., Watanabe, K., Kuribayashi, K., Shiraishi, Y. 1999. Autonomous Control for an Omnidirectional Mobile Robot with the Orthogonal-Wheel Assembly (In Japanese). *J Robot Soc Japan*. 17(1): 51-60.

[13] Ye, C., Ma, S., Hui, L. 2011. An Omnidirectional Mobile Robot. *Sci China Inf Sci*

[14] Ren, C., Ma, S. 2014. A Continuous Dynamic Model For An Omnidirectional Mobile Robot. 2919-24.

[15] Ferriere, L., Raucent, B. 1998. ROLLMOBS, A New Universal Wheel Concept. *Proceedings 1998 IEEE Int Conf Robot Autom*. 877-882.

[16] Ghariblu, H. 2010. Design and Modeling Of A Ball Wheel Omni-Directional Mobile Robot. *Second International*

Conference on Computer Engineering and Applications. 571-575.

[17] Ishida, S., Miyamoto, H. 2010. Ball Wheel Drive Mechanism for Holonomic Omnidirectional Vehicle. *World Automation Congress*.

[18] Mascaro, S., Asada, H. H. 1998. Docking Control of Holonomic Omnidirectional Vehicles with Applications to a Hybrid Wheelchair/Bed System. *Proc of IEEE Int. Conf. on Robotics and Automation*. 399-405.

[19] Wada, M., Takagi, A., Mori, S. 2000. A Mobile Platform with a Dual-wheel Caster-drive Mechanism for Holonomic and Omnidirectional Mobile Robots (in Japanese). *J Robot Soc Japan*. 18(8): 1166-72.

[20] Ok, S., Kodama, A., Matsumura, Y., Nakamura, Y. 2011. SO(2) and SO(3), Omni-Directional Personal Mobility With Link-Driven Spherical Wheels. *IEEE/RSJ Int Conf Intell Robot Syst.* (2): 268-73.

[21] Tadakuma K., Tadakuma R. 2007. Mechanical Design of "Omni-Ball": Spherical Wheel for Holonomic Omnidirectional Motion. *Proc of IEEE Int Conf. on Automation Science and Engineering*. 788-794.

[22] Nagarajan, U., Mampetta, A., Kantor, G., Hollis, R. L. 2009. State Transition, Balancing, Station Keeping, and Yaw Control for a Dynamically Stable Single Spherical Wheel Mobile Robot. *2009 IEEE Int. Conf. Robot Autom*. 2: 998-1003.

[23] Chen, W. H., Chen, C. P., Tsai, J. S., Yang, J., Lin, P. C. 2013. Design and Implementation of a Ball-driven Omnidirectional Spherical Robot. *Mech Mach Theory.* 68(1): 35-48.

[24] Nishikawa, A., West, M,. and Asada, H. 1995. Development of a Holonomic Omnidirectional Vehicle and an Accurate Guidance Method of the Vehicles (In Japanese). *J Robot Soc Japan*. 13(2): 249-256.

[25] Hirose, S., Amano, S. 1993. The VUTON: High Payload, High Efficiency Holonomic Omni-Directional Vehicle. *Proc of 6th Int Symp on Robotics Research.* 253-260.

[26] Damoto, R., Cheng, W., Hirose, S. 2001. Holonomic Omnidirectional Vehicle with New Omni-Wheel Mechanism. *Proc of IEEE Int Conf on Robotics and Automation*. 773-778.

[27] Wada, M. 2000. A Synchro-Caster Drive System for Holonomic and Omnidirectional Mobile Robots. *Proc of IEEE 26th Annu. Conf. of the Industrial Electronics Society.* 1937-1942.

[28] Wada, M., Mori, S. 1996. Holonomic and Omnidirectional Vehicle with Conventional Tires. *Proc of IEEE Int Conf on Robotics and Automation*. 3671-3676.

[29] Wada, M., Mori, S. 1996. Modeling and Control of a New Type of Omnidirectional Holonomic Vehicle. *4th International Workshop on Advance Motion Control*. 265-270.

[30] Han, F., Yamada, T., Watanabe, K., Izumi, K. 2000. Construction of an Omnidirectional Mobile Robot Platform Based on Active Dual-wheel Caster Mechanisms and Development of a Control Simulator. *J. Intell Robot Syst*. 29(3): 257-75.

[31] Yu, H., Spenko, M., Dubowsky, S. 2004. Omni-directional Mobility Using Active Split Offset Castors. *ASME J. Mech.* 126(7): 822-9.

[32] Wada, M. 2009. Mechanism and Control of a 4WD Robotic Platform for Omnidirectional Wheelchairs. *IEEE/RSJ Int. Conf. Intell Robot Syst.* 4855-4862.

[33] Ueno, Y., Ohno, T., Terashima, K., Kitagawa, H. 2009. The Development of Driving System with Differential Drive Steering System for Omni-Directional Mobile Robot. *Int. Conf. Mechatronics Autom.* 1089-1094.

[34] Wada, M., Asada, H. 1998. Design of a Holonomic Omnidirectional Vehicle Using a Reconfigurable Footprint Mechanism and Its Application to a Wheelchair (In Japanese). *J Robot Soc Japan*. 16(6): 816-823.

[35] Wada, M. 2007. Modeling and Control of Omnidirectional Mobile Robots with Active Casters (In Japanese). *J Robot Soc Japan*. 25(7): 1100-1107.

[36] Safar, M. J. A., Watanabe, K., Maeyama, S., Nagai, I. 2014. Tip-over Stability Enhancement for Omnidirectional Mobile Robot. *International Journal of Intelligent Unmanned Systems*. 2(2): 91-106.