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Comparative Analysis of Mobile Robot Wheels Design

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***Abstract*—This paper considers a design of wheeled mobile robot platforms. Each platform is designed for a set of specific tasks and thus is supposed to work in previously known general conditions of its environment. A robotic system could be constructed as a holonomic or a non-holonomic system, which directly correlates with a type of its wheels. In this work we compare different types of mobile robot wheels, including conventional wheels, universal omnidirectional wheels, Mecanum wheels, caster wheels, and steering standard wheels, and analyze the best scenario of design application. This paper shares our experience in selecting wheeled platform design and could be considered as a brief practical guideline for beginners in mobile robot platform design.**

***Index Terms*—Mobile robotics, comparison, omni drive, robot platform, robot design, engineering**

I. Introduction

Robotics field is rapidly developing, and robots are gradually becoming an important part of everyday life of humankind. Besides such classical areas as industrial [1], medical and rehabilitation robotics [2], which mainly use various manipulators with certain task-oriented end effectors while both a task and an operational environment could be a-priori described rather precisely, robotics gradually takes its place in less predictable fields such as, for example, human robot interaction [3], exploration [4] and urban search and rescue [5]. In nowadays robots are applied not only in factory settings, surgery operational rooms and warehouses, but interact with a human on a daily basis inside usual premises, including offices, hotels, corridors of hospitals and living apartments. Often in such settings mobile robots require a capability to operate in a confined space [6]. One of the natural selections for confined space operating in human-oriented environments today are bipedal robots, but their development and especially dynamically stable locomotion algorithms, fall detection and management [7] require significantly more efforts than a development of conventional wheeled robots that could move freely in confined spaces.

The analysis of research papers and real world applications demonstrates that a vast majority of modern mobile robots are constructed using wheels. However, this requires to consider maneuverability and controllability of a robot within its target environment at early design stages. Among the variety of options for number of wheels, their type and configuration within a mobile robot platform base a designer should select a most suitable one. To provide a good maneuverability of a mobile robot in a narrow space, omnidirectional wheeled solutions should be considered.

This paper explores a question of a wheeled mobile robot base design from a locomotion point of view tackling the choice of wheels and their configuration. We consider holonomic and non-holonomic robots and the corresponding types of wheels: conventional wheels, steering wheels, caster wheels, universal wheels, and Mecanum wheels. Next, we discuss particular strengths and drawbacks of each type providing useful technical parameters that could serve as a recommendation for a robot designer while selecting mobile robot locomotion modes. We do not pretend to cover all existing models and modifications of wheels (e.g., we do not deepen into multiple modifications of Mecanum wheels [8] or the newly created omnidirectional wheels [9]) within this paper due to space limitations, but we do demonstrate the most popular and widely used type of wheels and platform designs.

The rest of the paper is organized as follows. Section II reviews typical wheels of a mobile robot with a brief overview of their main advantages and disadvantages. Section III describes optional wheel configurations within a mobile robot base. Section IV provides a comparative analysis of these typical wheels. Finally, we conclude in Section V.

II. Holonomic and Non-holonomic systems

First we need to distinguish between holonomic and non-holonomic systems. A system is called holonomic if a number of controlled degrees of freedom (DoF) is equal to a total number of DoF [10]. Therefore, a robot is a non-holonomic system if a number of its controlled degrees is less than a total number of DoF. The property of holonomicity directly depends on the type of robot wheels. Consider a non-holonomic car-like robot, which is typically an Ackerman wheeled system that cannot move freely in any direction. At the same time a robot, which is equipped with omnidirectional wheels, becomes holonomic. This section describes holonomic and non-holonomic systems in terms of wheels usage as well as strengths and weakness of each type of wheels. In this paper we look at differential drive robots and Ackerman drive robots as representatives of non-holonomic systems, and consider caster wheels (including a caster ball), universal

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wheels, Mecanum wheels, omnidirectional wheels) as the ones to support holonomic system examples.

A. Conventional Wheel

One of the examples of a non-holonomic system is a differential drive wheeled robot with conventional wheels. A conventional wheel (Fig. 1a) is widely used in all engineering areas due to its simplicity and functionality, which is limited to providing forward and backward rotation of a wheel. For a differential drive robot conventional wheels allow robot rotation when different rotation speeds and/or rotation direction are applied for its conventional wheels.

B. Steering Wheel

At a first glance a steering wheel may look completely like a conventional wheel, but it has a different mechanical structure. The term steering means not just a wheel, but a certain steering mechanism, which allows a conventional wheel to rotate around its vertical axis. For this purpose, a mechanism uses a steering motor to control a movement direction (i.e., a rotation around the vertical axis) of a wheel, and a driving motor to provide forward and backward locomotion. This way, the same physical wheel could be used in the role of a conventional wheel or, by attaching a steering mechanism, it could be transformed into a steering wheel.

C. Caster Wheel

Another type of a wheel is a caster (or sometimes called *castor*) wheel (Fig. 1b2). Caster wheels have a wide application not only in robotics, but are also used in service and medical equipment, manufacturing etc. Using caster wheels helps to achieve a near-omnidirectional mobility of a mobile robot or any other mechanical vehicle. Some manufacturers divide caster wheels strictly into two categories: rigid wheels and swivel wheels. In the case of a rigid wheel, the wheel can rotate only forward and backward. For a swivel wheel category, the wheel can passively rotate 360 degrees with regard to the vertical axis as well as to rotate forward and backward, providing a free movement of the wheel. A special type of a caster wheel is a ball caster wheel (Fig. 1b1), which provides a free motion in all directions due to the use of a passive sphere in a role of a wheel. Ball caster wheels are widely used as additional passive wheels with other active driving wheels, e.g., it could be used to provide an additional ground-contact (rolling) point within a differential drive based platform.

D. Universal Omni Wheel

The basic idea of an omni wheel is a combination of a main active wheel and passive freely rotating rollers. The active wheel and the rollers have their own rotation axes and in the case of universal wheels, axes of passive rollers are orthogonal to a main wheel axis [11]. While an active wheel is rotating in clockwise or counterclockwise direction with respect to its rotation axis, combining active rotation of several active wheels with passively rotating rollers allows supporting locomotion almost in any direction. Typically, rollers have a cylindrical shape (Fig. 1c) and their number may vary. Even though omnidirectional wheels provide free locomotion in a 2D space, they have a number of disadvantages (e.g., inefficiency at a dirty surface) which are considered in the next Section.

E. Mecanum Wheel

These wheels are similar to a universal wheel construction except that rollers are mounted with their axis at an angle of 45 degrees relatively to an axis of an active wheel base (Fig. 1d). It was first developed by a company Mecanum AB in 1973 by Bengt Ilon [12]. Since a mecanum wheel design is complex, manufacturing cost is greater as compared to universal wheels. These wheels are capable to roll about an axis of an active wheel (i.e., a base wheel) and also about axis of rollers at an angle of 45 degrees. Applying different velocities to each wheel a robot can move in any direction; classic Ilon wheels have 3 Degree of freedom: wheel rotation, roller rotation, and rotational slip about the vertical axis passing through a point of contact with locomotion surface [11]. Thus, Mecanum wheels can move in a desired direction, allow a diagonal movement with regard to heading direction and a rotation around a robot vertical axis in place. More details about strengths and drawbacks of wheel be considered in the next sections.

III. Analysis of Wheel Configuration

In this section we demonstrate a number of examples for possible wheel configurations. While there are no limitations for a number of wheels or their placement within a mobile robot base, the following schemes reflect most broadly used by robotics community configurations due to their optimal designs.

A. Conventional Wheel and Caster Wheel

Caster wheels are used as passive wheels and they can be applied together with other wheels to reach omnidirectional mobility. One of the popular configurations for using such

Fig. 1. Wheel types: (a) a conventional / steering wheel, (b1) a caster ball wheel, (b2) a caster wheel, (c) a universal wheel, (d) a Mecanum wheel.

wheels is a differential drive robot; conventional wheels are used as active wheels and a caster wheel adds stability to a robot, providing a triangular support polygon, and is used to allow free rotation (Fig. 2).

B. *Steering Wheel*

Steering wheels name comes from their steering mechanism, which acts through a drivetrain mechanism of a robot. Thus, a steering motor controls a steering direction (to the left or to the right) of the wheels and this way a motion direction, while a drive motor transfers a torque to the wheels to provide forward and backward movement.

Steering wheels are typically used in four-wheeled (e.g., car-like robots, Fig. 3a, b, c), three-wheeled (e.g., triangular cart-like platforms, Fig. 3d) and two-wheeled configurations (e.g., bicycle). For a three-wheeled configuration it is popular to combine two active steering wheels with a single caster wheel in a role of a passive wheel (Fig. 3d)

C. *Universal Omni Wheel*

A configuration can be optimally composed using three of four wheels. Three universal wheels could be mounted on a triangular platform with their axes being inclined by 120 degrees relative to each other (Fig. 4a and Fig. 6, left).

In four-wheeled design two configurations are typical:

1) Wheels are located symmetrically on the sides of a square mobile platform base (Fig. 4b) with the 90 degrees angle between the wheels
2) Wheels are located symmetrically at the corners of a square mobile platform base and their axes are inclined by 90 degrees relative to each other (Fig. 4 c) [13]

Examples of such universal wheels designs could be found in [14], [15].

D. *Mecanum Wheel*

With Mecanum omnidirectional wheels a typical platform has a rectangular or a square shape and the wheels are located in a car-like style (Fig. 5, Fig. 6 right): they are mounted in-line to each other. While usually robots use four Mecanum wheels, this is not a strong limitation [16], [17], [18], [19], [20] [21].

IV. Wheels Comparison

In this Section we compared certain type of wheels and make analysis of strengths and drawbacks of each type of wheels. For comparison we will use following type of wheels: conventional wheels, universal wheels, Mecanum, steering

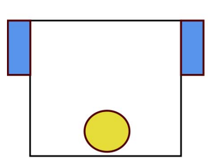

Fig. 2. Configuration of a differential drive robot with conventional wheels and a passive caster wheel.

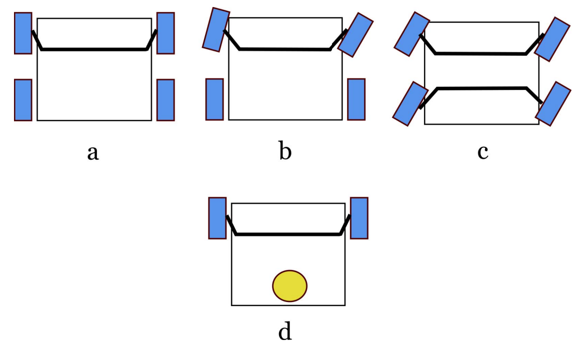

Fig. 3. Steering wheels configurations: (a) a generic view of configuration, (b) an Ackerman drive configuration, (c) a near omni drive configuration, (d) steering wheels and a caster passive wheel.

wheels and caster wheels. While comparing the wheels we emphasize the two following points:

- Physically conventional wheels and steering wheels are the same, but they differ in mechanical parameters
- We do not explicitly distinguish caster wheels and ball caster wheels (spherical wheels)

For our comparison we selected general mechanical properties: manufacturing complexity [11], sensitivity to a rough surface, sensitivity to small (extraneous) objects on the surface [13] [19], possible wheels configuration (guided by the configurations that we have discussed earlier in the paper) [13], minimal required quantity of wheels (minimal quantity of sufficient robot configuration) and degrees of freedom (DoF). Next, we compared two technical parameters of wheels and investigated the approximate values using technical information in websites of wheel manufacturers and their suppliers [22], [23], [24], [25]. For reader convenience, we present the results in three separate tables.

Table I presents the results of comparison of general parameters of different wheel types. For such parameters as sensitivity to floor conditions and manufacturing complexity simple wheel types (conventional, steering, and swivel caster) provide the best solution. They do not have complex design and are almost robust for rough surface of up to some degree of roughness. At the same time, ball caster wheels are sensitive to small objects that may appear on a locomotion surface because a space between a spinning sphere and its cap may be clogged

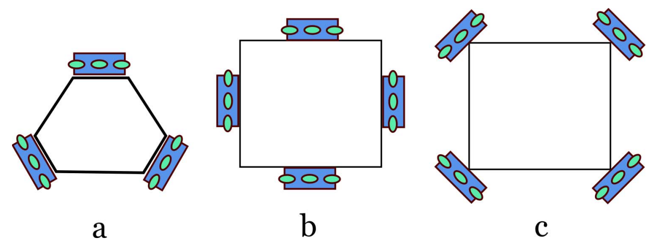

Fig. 4. Universal wheel configurations: (a) triangular base; (b) square base, wheels are on the sides; (c) square base, wheels are at the corners.

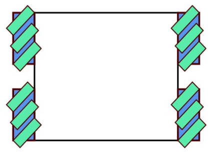

Fig. 5. Configuration of Mecanum wheels.

TABLE I
GENERAL PARAMETERS OF WHEELS

Type of a wheel	Manufacturing complexity	Sensitivity to a rough surface	Sensitivity to small objects on a surface
Conventional	Low	Low	Low
Steering	Low	Low	Low
Caster wheel	Low	Low	Low
Caster ball	Low	Low	High
Universal	Medium	High	High
Mecanum	High	High	High

TABLE II
MECHANICAL PARAMETERS OF WHEELS AND CONFIGURATIONS

Type of a wheel	Possible wheels configuration	Minimal required number of wheels	DoF
Conventional	2 or more wheels	2	1
Steering	2 (+1 DW) 3, 4 wheels	2 (+1 DW)	2
Caster	1 (as PC)	1 (as PC)	1, 2, 3
Universal	3 or 4 wheels	3	3
Mecanum	4 or more wheels	4	3

TABLE III
TECHNICAL PARAMETERS

Type of a wheel	Minimum required diameter	Maximum load
Conventional and steering	50,8 mm	Up to 40-60 kg
Caster	25,4 mm	15 kg
Universal	101,6 mm	2-30 kg
Mecanum	101,6 mm	7-15 kg

with small particles.

Table II compares mechanical parameters of wheels and their configurations. In the second and third columns DW denotes other (different) wheels, while PC means that a wheel is considered through a prism of being a part of a complicated configuration with other (different) wheels. A conventional wheel has only one degree of freedom (moving forward and backward), but requires at least two wheels in a case of differential drive robot and actually does not have upper limits on a number of wheels to be integrated into a mobile platform base. However, conventional wheels cannot provide an omnidirectional mobility. Steering wheels have two degrees of freedom (moving forward and backward, and a rotation around a vertical axis) and can be used in several configurations: two wheels (e.g., with an additional passive caster), three wheels (as synchronized wheels), and four wheels as car-like robot. A caster wheel type contains three different types and each type has its own degree of freedom value. A caster ball has 3 degrees of freedom due to its design, but can be implemented only as a passive wheel. A swivel caster has two DoF and is also used as a passive wheel only. The third type of a caster (a rigid wheel) has only one DoF. Omnidirectional wheels have 3 DoF: universal wheels provide configuration of three or four wheels, while a Swedish wheel is optimally used in car-like wheels arrangement for four wheels.

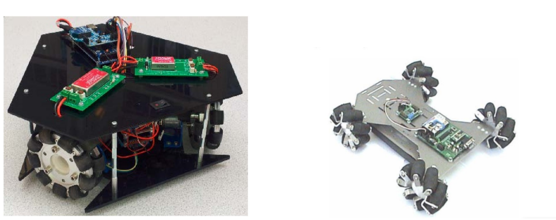

Fig. 6. Example of omni drive robot platform using three universal wheels [14] (left) and four Mecanum wheels [20] (right).

Table III contains technical information about wheels that can be useful for designing a mobile robot model. Each wheel type has some minimal diameter and maximum load capacity. We selected these parameters because they determine the possible degree of load on the wheels from the robot mass and also indicate minimum required wheel's size for platform construction. Such information is need to construct mobile platform design properly with desired weight of a platform. Again, a conventional wheel has the best load capacity due its simple design, while omnidirectional wheels are more sensitive to maximum load parameter.

Thus, each type of a wheel has its own strengths and drawbacks. Conventional wheels are very reliable and robust, but do not provide a free locomotion in any direction as omnidirectional wheels do. Omni wheels are an excellent choice to ensure robot's maneuverability in indoor and narrow space, but are probably the worst choice for outdoor tasks. Caster wheels are an optimal and simple way to support a more free locomotion for classical wheels (conventional and steering). All of the above-mentioned wheels have preferable configurations for designing a mobile platform. However, at the beginning stages of a new mobile platform design the major questions are determining a working environment of the robot, its intended tasks and an approximate robot weight while being fully loaded. The answers for these questions will allow a correct selection of wheel arrangement, type and sizes.

V. CONCLUSIONS

In this paper we compared certain types of wheels: conventional wheel, steering wheel, caster wheel, Mecanum wheel and universal wheel to facilitate the question of selecting the most suitable wheel type and configuration for constructing a mobile platform. We selected mechanical parameters and technical values to investigate the question of existing strengths and drawback of each type. The general and mechanical parameters for the comparison included manufacturing complexity, sensitivity to a rough locomotion surface, sensitivity to small (extraneous) objects on a locomotion surface, possible wheels configuration, minimal required number of wheels and degrees of freedom. For the second comparison we selected minimal required size and maximum load capacity. As a result, each type of a wheel has its own strengths and drawbacks. Conventional wheels are robust, but do not provide such maneuverability as omnidirectional wheels. However, omni wheels have complex manufacture design and high sensitivity to locomotion surface conditions. Therefore, the first step of designing and selecting the wheels is awareness of further robots workspace and application area.

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