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Feasible utilization of the inherent characteristics of holonomic mobile robots

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HIGHLIGHTS

- A feasible method was developed to handle the mechanical capabilities of omniwheeled robots.
- The proposed algorithm conforms to the current, widely used robot control architectures.
- A simulation of dynamic characteristics was published to assist robot design.
- The simulation and experimental measurements confirmed the theoretical results.
- A Robot Operating System package was implemented and is accessible online.

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ABSTRACT

This paper presents a computationally inexpensive generic method to utilize the maximum velocity and acceleration of an omnidirectional mobile robot. The proposed method is based on the inverse kinematic and inverse dynamic models by defining novel velocity and acceleration reserve multipliers respectively. The defined multipliers enable a computationally inexpensive solution and give representative index numbers, showing the amount of utilized resources during online computation. The model was applied to control a kiwi drive mobile robot and validated by experimental measurements. An open-source Robot Operating System (ROS) catkin C++ package was published to enable the feasible implementation of the results.

1. Introduction

The first three-wheeled holonomic platform appeared in 1994, developed by Stephen Killough and Francois G. Pin [1]. Killough's design used three pairs of wheels mounted in cages, orthogonal to each other, and thereby achieved holonomic movement without using true omniwheels. Fig. 1 shows the platform employing three omnidirectional wheels (instead of actuated caster wheels [2,3]) in a triangular formation, which is generally called kiwi drive.

After Killough's patented invention, several researches focused on the modeling and control of these holonomic platforms. The kinematics were first described by Killough, and the dynamics are presented in many different forms. The path tracking for these robots is developed using different methods: Vazquez and Velasco-Villa derived the computed-torque control for omnidirectional robots [4]. Kiattisin Kanjanawanishkul and Andreas Zell solved the path-following problem with model predictive control [5]. The sliding mode control based approach can also be used, especially on systems including transport delay [6]. Moreover, an integral sliding mode control based method is also known [7]. The trajectory generation for omnidirectional vehicles is also developed for time optimal control solutions [8–10]. Nowadays, holonomic platforms are used in industry and households, e.g. Mecanum wheel based forklifts or security robots.

Regarding results in general for the generation and tracking of time optimal trajectory, most methods apply constant velocity and acceleration limits to the robot body. Only a few of the methods deal with the possible maximum velocity and acceleration of the robot, which is rapidly changing during motion. Surprisingly, there are cases when the robot can go faster in a direction if it rotates during linear movement [11]. As an illustrative example, Fig. 1 shows a front- and a rear-wheel driven case, where the possible maximum acceleration (and deceleration) difference is often twofold.

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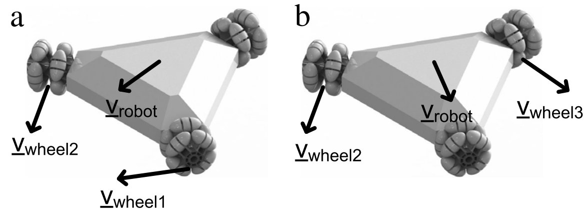

Fig. 1. Front- (a) and rear- (b) wheel driven cases of a kiwi drive mobile robot platform, where $\underline{V}_{wheel}$ is the constrained driving velocity of the wheels and $\underline{V}_{robot}$ is the linear velocity vector. Due to robot dynamics, maximum acceleration of the robot is higher in case (b).

1.1. Previous results focusing on the mechanical capabilities of holonomic robots

In 2002, Robert L. Williams II, Brian E. Carter, Paolo Gallina and Giulio Rosati [12] proposed the extensive modeling of holonomic movement considering wheel-slip. However, their work mostly focused on the slip caused by a single row omniwheel, which is designed for material handling industrial applications instead of mobile robots. They included the latter friction case for handling the non-continuous rolling surface of the single wheel. They assumed that the robot weight is equally distributed on each wheel, which neglects the effect (showed by Fig. 1) when the robot operation is similar to a front- or rear-wheel driven vehicle.

André Scolari Conceicao, A. Paulo Moreira, Paulo J. Costa presented a method in 2006 for time optimal velocity control that considers the maximum wheel speeds [13], called ideal reference velocities (IRV). This IRV method can be adapted and may work for the dynamics too, but it causes too many different equations for different wheel arrangements. The solution can be very difficult, especially when the robot is over-actuated by four or more wheels. In this paper, a similar method is presented, which gives the same end results for the ideal velocity command but with a different and easier-to-implement approach: There is no need to express anything from inverse kinematic equations and no need to rearrange any of them. The IRV method defines a "factor of scale" variable marked with α. This factor can be calculated by simply writing the original velocity vector's components into the inverse kinematic equations, and the results are the required wheel speeds. After that, the allowable maximum wheel speed has to be divided by these values to get α. Therefore, in this paper, α is not only known as a factor of scale but has more meaning and is called velocity reserve multiplier, marked with λ. In case of dynamics, it is called acceleration reserve multiplier, marked with σ.

Also in 2006, Jianhua Wu, Robert L. Williams II and Jae Lew [11] first presented phase spaces as velocity and acceleration cones for kiwi drives. The cones were derived with linear transformations using kinematic and dynamic models. The form of the velocity cone is correct, but in case of the acceleration cone, they assumed continuous equal weight distribution on all wheels, therefore their cubic shape model should only be used when the vertical position of the center of gravity (CoG) is close to the ground, otherwise it can easily cause wheel-slip. The same disadvantageous simplification can be found in the dynamic modeling in [9,12,14–16].

In 2008, Chuntao Leng, Qixin Cao and Yanwen Huang [17] made an improved artificial potential filed (iAFP) method for a four-wheel omnidirectional robot. This publication was the first that considered the distinct load forces on the wheels during acceleration. Instead of using phase-space, they derived an anisotropic function to deviate the original output result of the dynamic AFP method.

1.2. Conforming with current high-level control platforms

A number of proposals [8,10,18] handle the non-linearity of the robot in different ways, but there is no practical approach that investigates the robot dynamics itself and provides information on the limits for a feasible and robust implementation. The goal of this research was to define a reusable theory which conforms the existing, widely used mobile robot control practices, while being eligible for effortless and run-time efficient implementation.

The current high-level robot control platforms, such as Robot Operating System (ROS) [19] or Mobile Robot Programming Toolkit (MRPT) [20], are presently using constant limits. ROS and MRPT support velocity control mode by assigning a new velocity command to a mobile robot platform at each predefined time period. In fact, the decision about a new velocity command is not the result of an exact trajectory calculation as in the field of industrial robotics. Several online decision methods provide the new velocity reference based on real-time environment sensors data. The operation of these online reactive navigation methods is not strongly bounded to velocity and acceleration limits. The interpolation of a CNC machine fails to follow the exact trajectory if one of these boundary conditions are changed online. But practically, ROS has a local planner algorithm [21], which uses Dynamic Window Approach (DWA). DWA is not sensitive to parameter changes: it samples from the set of achievable velocities for just one simulation step given by the acceleration limits of the robot. Also, MRPT uses a Nearness Diagram (ND) Navigation [22] for obstacle avoidance, which is a perception–action process, and it can simply work with updated velocity and acceleration limits as long as the limits are never set to zero.

The velocity limits are driven by the maximum speed of the wheels. Regarding the acceleration limits, the wheel-slip, the tip-over situation and the maximum motor torque need to be taken into account. The overall result of these limits can also be given to the high software level control in each command cycle as the allowed codomain of the new velocity command. This approach is necessary in order to make the best use of the inherently changing characteristics of the robot in applications that require online path planning.

1.3. Structure of the paper

The paper is arranged in the following way: Section 2 gives a short overview on the proposed phase space for velocity and acceleration and shows the valuable difference compared to the prevalent unidirectional modeling. Section 3 describes the robot kinematics and the maximum velocities of the robot. After that, the dynamics and the maximum accelerations are calculated by each boundary in the following order: wheel-slip, motor torque and tip-over situation. At the end of this chapter, the visualization of the acceleration space is presented. Section 4 includes the evaluation of the experimental results. Then it presents the realization of the developed algorithms on a kiwi drive based mobile robot platform using a custom ROS package. Finally, Section 5 summarizes the conclusions.

The following conventions are used in the equations for marking scalars, vectors and their absolute value: Vectors are underlined (if not, that represents their absolute value). If the label of a vector is not underlined but has subscript, it represents one component of the vector.

2. Proposed phase space

General time-optimal theories in the field of ground vehicles and mobile robots often use the friction circle model to model wheel-slip [23]. But as the simple illustration of Fig. 1 shows,