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Estimation of the instantaneous centre of rotation with nonholonomic omnidirectional mobile robots

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HIGHLIGHTS

- Compliant steering actuators usually do not define well the ICR, which needs to be estimated.
- A new ICR estimation algorithm working in the steering actuators' space is proposed.
- It is designed for platforms with centred and sidewards off-centred wheels.
- The proposed algorithm gives a better estimation compared to other alternatives.

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ABSTRACT

In order to move safely and accurately, mobile platforms using steerable wheels require adequate coordination of their actuators. One possibility to achieve actuator coordination is to control the motion of the chassis' instantaneous centre of rotation (ICR) and motion around it. Considering the chassis as a rigid body, the ICR is located at the intersection of each wheel's zero motion axis. In practice however, these axes may not concur, in particular when compliant actuators are used for wheel steering. They then no more define precisely an ICR and only an estimation of its position can be computed. Moreover, most parametrizations of the ICR position bring in singularities with no physical meaning, which hinder estimation. This paper introduces the H representation, a new parametrization of the motion state space free of any non-structural singularities, and presents an algorithm which estimates the ICR within the joint space. The proposed approach is compared in terms of reliability, efficiency, accuracy and robustness with three methods working within the operational space. Results suggest that the proposed estimation approach provides the best compromise for these performance indicators.

1. Introduction

Omnidirectional mobile platforms can move in any direction without manœuvring, making them suitable for operation in tight areas and crowded spaces. One mechanism to provide such capability are omnidirectional wheels, like wheels made with passive rollers attached along their circumference [1]. Steerable wheels are another alternative, allowing a platform to move in any direction by only changing the orientation of its wheels. Compared to omnidirectional wheels, the use of steerable wheels provides more precise odometry and lower mechanical complexity [2]. Many platforms use steerable wheels, like Meka B1 [3], the EXOMARS rover [4], Willow Garage PR2 [5], Rollin' Justin [6,7], Care-O-bot [8–10] and AZIMUT [11–13]. Yet, omnidirectional platforms using steerable wheels are nonholonomic, since the wheels need to be reoriented to change the direction of motion. The wheels thus constrain the chassis motion and need to be carefully coordinated for the platform to move [14] without generating high internal forces and slippage caused by actuator antagonism [7,12,15]. To handle this coordination, motion of the individual actuators must be linked through kinematic models with the motion of the chassis, which may be described using two paradigms: the chassis' twist (instantaneous linear and angular velocities) or the chassis' motion around its instantaneous centre of rotation (ICR). In the case of a rigid body undergoing planar movement, the ICR is the point in the body's referential frame which has zero velocity at a given instant in time. Since steerable wheels can only move in the wheel plane, the zero motion axis (i.e., the axis perpendicular to the wheel plane and going through the wheel's centre, called hereafter propulsion axis) of each of the platform's wheels should then concur at the ICR location [16].

The twist paradigm is often used to control motion of robots using steerable wheels and is adapted to control quasi-holonomic

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platforms (e.g., using active caster wheels), since the twist components then provide independent control inputs [2]. When considering purely nonholonomic platforms, however, the direction of motion cannot change instantly and the twist components then become linked to each other, making it difficult to only use the twist paradigm [15,17]. As an alternative, the ICR paradigm provides independent control inputs: the ICR position and the motion around the ICR. ICR-based control enforces the nonholonomic constraints, since the propulsion axes must intersect at the ICR location for the platform to move safely and accurately. It thus provides an abstraction of the platform's actuators for control [18] that also enables easy recovery of the instantaneous physical state of the platform when needed. Without chassis motion, motion of the steering actuators can still be controlled by moving the desired ICR, for example to make very sharp turns that require the robot to stop and reconfigure its wheels' position, whereas a null twist gives no information to control steering and a separate control algorithm is needed to do the reconfiguration. In addition, the kinematic models of platforms using steerable wheels exhibit structural singularities when the ICR is on a steering axis [7,14,15]. Using the ICR paradigm makes it possible to define these singularities with a minimal number of conditions (i.e., the number of steerable wheels), whereas using the twist paradigm requires checking an infinite number of conditions, which complexifies the design and implementation of a motion controller. Hence, even though motion control of nonholonomic platforms is possible using the twist paradigm [19], switching to the ICR paradigm is beneficial to easily handle structural singularities [7].

Using the ICR paradigm also brings challenges to overcome:

1. Most ICR parametrizations introduce singularities that are not related to singularities in the chassis motion, such as undefinedness of direction at infinity (for 2D Cartesian coordinates), undefinedness at the pole (for polar and spherical coordinates) or discontinuities in a parameter when crossing some meridian (for spherical coordinates) [17]. Those parametrization-induced singularities need to be dealt with and a singularity-free parametrization could provide more efficient and simpler ICR determination and motion control.
2. The ICR is a mathematical concept which enables abstraction of the platform geometry and actuators, but the only available source of information to determine its location – which is needed for ICR-based motion control – are the actuators' sensors. With infinite stiffness actuators, perfect sensors and careful coordination, the assumption of the complete robot (chassis and wheels) as a single rigid body would hold and the propulsion axes would concur at the ICR location. However, a real robot is always imperfect: it has geometric imperfections, actuators with finite stiffness, stiction and limitations, as well as sensors with noise and quantification. The robot should then be considered as a rigid body (the chassis) connected to rigid bodies (the wheels) that can move wrt the chassis, and the propulsion axes may not create a well-defined intersection when considering robots with three or more steerable wheels. This phenomenon is only made evident after long experimentation times with stiff actuators [7,8]. But when compliant actuators are used for wheel steering to help minimize actuator antagonism or to make the robot more responsive and secure to physical contacts, like with AZIMUT-3 [12,20], this is always perceptible. In that case, the ICR location still exists, but it cannot be determined *directly* by the actuators' sensors. In practice however, since motion of the platform is happening, the propulsion axes must have globally a minimal deviation from the ICR location, which has been confirmed by experimentation [21]. Compliant actuators bring the challenge that the propulsion axes do not have a well defined intersection during motion, but also help cope with that fact by ensuring that minimal deviations do not create actuator antagonism leading to slippage. Thus, as long as motion control ensures a careful coordination of the actuators and is fed with the most reliable ICR position, the ICR-based control model stays valid. Determining the most reliable ICR position may be done either in the operational space or in the joint space. Using a least squares estimation (LSE) in the operational space is standard practice [22], but it has been shown this does not give the most reliable ICR estimation when the propulsion axes are close to parallel [21]. As an alternative, an Extended Kalman filter (EKF) has been used in [4], but according to its authors, it does not give better results than the algorithm proposed in [21], which works in the joint space.

The aim and contribution of this paper are to present an approach for ICR estimation that addresses these challenges. It starts with the definition of a new parametrization of the ICR position having its roots in projective geometry and free of parametrization-induced singularities, and an associated representation in $\mathbb{R}^3$. We collectively refer to the parametrization and representation as the H representation. An iterative ICR estimation algorithm working in the joint space, based on [21], then leverages the H representation properties to obtain the best possible estimation when the ICR is not well defined, i.e., the propulsion axes do not concur. That algorithm is compared to three other algorithms working in the operational space: one doing no estimation, one using a LSE and one computing the motion constraints' null-space. Their relative performance is evaluated in terms of reliability, efficiency, accuracy and robustness, demonstrating the benefits of using the proposed approach compared to the others evaluated. Demonstration of the applicability and usefulness of the proposed H representation and ICR estimation algorithm for ICR-based motion control of nonholonomic omnidirectional platforms is presented in [20,23,24].

This paper is organized as follows. Section 2 introduces the H representation for ICR representation and parametrization. Section 3 details the proposed ICR estimation algorithm and the three other algorithms used for comparison. Section 4 then presents their use on AZIMUT-3, an omnidirectional platform using four compliant steerable wheels, with results using simulated and real data.

2. Motion representation

As formulated by Campion et al. [16], a robot motion can be seen instantaneously as a rotation around the ICR. Using two-dimensional Cartesian ($\mathbb{R}^2$) or polar ($\mathbb{R} \times \mathbb{S}$) coordinates seems a natural choice for parametrizing its position. But those parametrizations have singularities with no physical meaning [17]. For instance, going from a slight right turn to a slight left one, as illustrated on Fig. 1, involves a continuous motion of the chassis but causes discontinuities in a two-dimensional Cartesian parametrization: the ICR position is near infinity on the right and goes directly to infinity on the left without going through the centre of the chassis. Even though they are not critical to handle, these singularities occur in a frequently used region of the state space and interfere with ICR estimation and motion control.

2.1. The real projective plane

Since the different regions representing infinity in $\mathbb{R}^2$ are not connected ($x = -\infty$ is not identified with $x = \infty$ and the same for y), parametrizing the ICR motion in $\mathbb{R}^2$ without singularities is impossible. A new two-dimensional topological space is