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Real-time constrained trajectory generation of mobile manipulators

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HIGHLIGHTS

- A class of non-linear mobile manipulator trajectory generators is proposed.
- The trajectory generation laws are shown to be finite-time stable.
- Collision-free motion generators providing bounded controls are also offered.
- The numerical simulations confirm theoretical results.

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ABSTRACT

This work offers the solution at the control feed-back level of the accurate positioning in a finite time of the end-effector whose mobile manipulator is subject to control and complex state constraints. We propose new forms of various terminal sliding modes (TSM's) which result from the access to kinematic redundancy of the non-holonomic mechanical system. In order to incorporate control and state inequality constraints into trajectory generation law, both a suitably defined extended task error is introduced and exterior penalty function approach is utilized. In addition, to incorporate holonomic singularity avoidance condition, collision avoidance constraints for the whole mobile manipulator and its final velocity, a suitably defined projection term onto the null space of the extended Jacobian matrix has been introduced. Control limits are maintained by suitable choice of trajectory generator gains. The numerical simulation results carried out for a mobile manipulator consisting of a nonholonomic differentially steered wheeled mobile platform and a holonomic manipulator of two revolute kinematic pairs, operating both in a two-dimensional unconstrained work space and work space including the obstacles, illustrate performance of the proposed trajectory generators.

1. Introduction

In recent years, an interest has increased in applying mobile manipulators to useful practical positioning tasks such as inserting a shaft into a bearing hole or an assembly of electronic components onto a small surface of printed circuit boards. These tasks require, by their nature, extremely high precision and stability of the performance. The aim of the positioning task is to find a desired (reference) trajectory, expressed in generalized coordinates, along which the mobile manipulator moves from its initial configuration and velocity to a desired end-effector location expressed in the task (work) space coordinates. As is well known [1], relationship between generalized coordinates and the task ones is strongly non-linear. The platform of the mobile manipulator, which is far from the desired end-effector location, has to shift to a preferable (not specified) posture, at which the end-effector attains desired location. As is known, no smooth time invariant state feed-back controllers exist for the platform accomplishing a point-to-point task [2,3]. However, by combining the mobility of the non-holonomic platform with the manipulability of the holonomic manipulator, performance characteristics of such a kinematically redundant mechanism (mobile manipulator) are improved which enable it to accomplish complicated tasks, e.g. accurate end-effector positioning in work spaces including many known and/or unknown obstacles, joint limit avoidance, and/or avoidance of singular configurations. In order to eliminate undesirable vibrations of the end-effector at the goal location which are usually caused by the kinematic redundancy of the mobile manipulator [4], its velocity and in particular the platform velocity has to be reduced to zero. Moreover, the holonomic manipulability measure, introduced by Yoshikawa [5], should be

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large at the end-effector location. Due to imposed aforementioned technological constraints, the mobile manipulator is required to accurately move in a finite time from the initial configuration and velocity to the desired end-effector location. The mobile manipulator velocity should be reduced at the desired location to zero also in a finite time. Furthermore, when moving in the work space with unknown obstacles, the mobile manipulator and the end-effector should avoid collisions. In addition, a desired trajectory is to be generated in such a way as to not bring about the violation of control constraints. Application of the mobile manipulators to the tasks mentioned above complicates their performance since such manipulators provide, in general, not unique solutions. Consequently, some objective functions are usually specified to solve such tasks uniquely. Minimization of the integral performance index is mostly considered in the literature [6–9].

1.1. Related works

Several approaches may be distinguished in this context. Works [6–9] deal with the optimal solutions of a point-to-point control problem subject to mobile manipulator dynamic equations and obstacles in the work space. Although the aforementioned approaches produce optimal (or suboptimal) solutions, they are not suitable to real-time computations due to their computational complexity. Therefore, it is natural to attempt alternative techniques if one wants to generate the mobile manipulator trajectory in real-time. Several approaches to controlling the mobile manipulators subject to both kinematic and dynamic equations were proposed in the literature. Nevertheless, all of them provide at most asymptotically stable solutions. In what follows, we give a brief survey of the two main approaches tackling the trajectory generation problems subject to both kinematic and dynamic equations. The first approach utilizes pseudo-inverse techniques to resolve mobile manipulator redundancy. Purely kinematic solutions have been proposed in works [10–15]. Incorporating both kinematic and dynamic equations into control law was presented in works [4,16–18], where the redundancy resolution is carried out at the torque/force level. The asymptotically stable control strategies from [4,18] generate collision-free trajectories when attaining the desired end-effector location. In our recent work [4], some attempt has been made to asymptotically stabilize the platform velocity to zero. The main disadvantage related with most of the known pseudo-inverse techniques applied to fulfil state inequality constraints is lack of obstacle influence on the end-effector movement. Consequently, the pseudo-inverse based algorithms have to provide explicitly or implicitly a collision-free end-effector trajectory to the corresponding controllers. This requirement seems to be very restrictive from the perspective of the end-effector positioning tasks. The second approach, developed in works [19–23], involves input–output decoupling controllers and both kinematic and dynamic equations. The algorithms from [19–23] require additional output functions and inverse of the so-called extended Jacobian matrix. From the literature survey, it follows that all the aforementioned trajectory generation algorithms are not able to shift the non-holonomic mechanical system in a finite-time in such a way as to fulfil control and state equality and inequality constraints subject to kinematic and dynamic equations.

1.2. Motivation of the approach

The present work addresses the problem of the finite-time generation of the trajectory for the mobile manipulators in real time subject to control and state variable constraints. Several approaches [24–31], which partially relate to a class of the finite-time control tasks may be distinguished. However, all those approaches deal only with stationary robotic manipulators, neglect their kinematic equations and cannot be applied to tasks with control and/or state inequality constraints resulting from both the physical limits of the actuators and the collision avoidance requirement. We first propose new forms of various terminal sliding modes (TSM's) which result from the access to kinematic redundancy of the non-holonomic mechanical system and are defined by useful tasks to be accomplished. Then, all the TSM's are simultaneously applied in both the reaching phase and the sliding phase, resulting in a new continuous TSM trajectory generator for mobile manipulators with finite-time stability provided that some practically reasonable assumptions are fulfilled. Our TSM's eliminate undesirable singularity problem related with the known TSM control algorithms [24–26]. Moreover, the methodology of multiple TSM's introduced here, generalizes the approaches known from the literature which were limited to a single TSM corresponding to position/velocity error. In order to incorporate control and state inequality constraints into trajectory generation law, a suitably defined extended task error is introduced which includes the following two components: position error and obstacle influences on the end-effector movements. In addition, to incorporate holonomic singularity avoidance condition, collision avoidance constraints for the whole mobile manipulator and its final velocity, a suitably defined projection term onto the null space of the extended Jacobian matrix has been introduced. In our approach, we apply the Lyapunov stability theory to design a class of simple non-linear trajectory generators solving the accurate end-effector finite-time convergent constrained positioning task. Fulfilment of control inequality constraints is carried out by suitable choice of trajectory generator gain coefficients. Because the trajectory generation scheme proposed here is implemented at the joint acceleration level, a joint position/velocity controller is assumed to be available (offered, e.g., in work [32]) that closely (or accurately) tracks any desired trajectory provided by our motion generator. Let us also note that generation scheme proposed here may be directly used to track the reference trajectories provided that dynamic equations of the mobile manipulator are known with sufficient accuracy. Kinematic and dynamic parameters can be obtained with sufficient accuracy by means of the calibration and identification techniques presented, e.g., in [33,34]. The remainder of the paper is organized as follows. Section 2 formulates the finite-time end-effector positioning task subject to collision avoidance with obstacles, holonomic singularity avoidance and limits on torques/forces, as a constrained trajectory generation problem. Section 3 sets up a class of non-linear motion generators solving the positioning task in a finite time, subject to control and state dependent constraints. Section 4 presents computer examples of the task accomplishment for a mobile manipulator consisting of a non-holonomic $(0, 2)$ platform and a holonomic manipulator of two revolute kinematic pairs, operating in both an unconstrained two-dimensional work space and a work space with obstacles. Finally, some concluding remarks are drawn in Section 5.

2. Problem formulation

Consider a mobile manipulator composed of a nonholonomic platform. It is described by the vector of generalized coordinates $x \in \mathbb{R}^l$, (platform posture $x_{1,c}$ $x_{2,c}$, θ and angles of driving wheels ϕ_1, ϕ_2—see Fig. 1, where θ is the orientation angle of the platform with respect to a global coordinate system Ox_1x_2; $x_{1,c}, x_{2,c}$ stand for coordinates of the platform centre; W denotes one half of the distance between platform wheels; $2L$ is the platform length; R stands for the wheel radius; (a, b) denotes the point at which the holonomic manipulator base is fasten to the platform) where $l \geq 1$ and joint coordinates $y \in \mathbb{R}^n$ of a holonomic manipulator mounted on the platform; n is the number of its kinematic pairs.