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Path-tracking velocity control for robot manipulators with actuator constraints[☆]

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ABSTRACT

An algorithm for high-performance path tracking for robot manipulators in the presence of model uncertainties and actuator constraints is presented. The path to be tracked is assumed given, and the nominal trajectories are computed using, for example, well-known algorithms for time-optimal path tracking. For online path tracking, the nominal, feedforward trajectories are combined with feedback in a control architecture with a secondary controller, such that robustness to uncertainties in model or environment is achieved. The control law is based on existing path-velocity control (PVC), or so called online time scaling, but in addition to speed adaptation along the tangent of the path, the algorithm also comprises an explicit formulation and approach, with several attractive properties, for handling the deviations along the transversal directions of the path. For achieving fast convergence along the normal and binormal directions of the path in 3D motion, the strategy proposed has inherent exponential convergence properties. The result is a complete architecture for path-tracking velocity control (PTVC). The method is evaluated in extensive simulations with manipulators of different complexity, and PTVC exhibits superior performance compared to PVC.

1. Introduction

The task considered in this paper is for a controlled mechanical system to follow a predefined geometric path. A path is a curve in space, whereas for a trajectory the curve is time-parametrized, or alternatively, a corresponding velocity profile is given. The fundamental difference between path tracking and trajectory tracking is consequently that the velocity along the path can be modified in the case of path tracking. Path tracking, or equivalently path following, is a fundamental control problem with many applications, and it is well-known for robot manipulators in tasks such as machining, welding, gluing, and cutting. In intelligent and/or autonomous systems it is customary with a decoupled approach, *i.e.*, to segment motion control in the levels of path planning and path tracking [1,2] in a hierarchical structure to reduce the complexity of the complete motion-planning problem. Therefore, path tracking is a major component in new developments in intelligent robotics, unmanned aerial vehicles (UAVs), and autonomous vehicles, and the current interest in robust algorithms for path tracking is considerable [3–5].

1.1. Trajectory tracking versus path tracking

One way of approaching path tracking is to consider it as the task of tracking a sequence of trajectory points for a vector $x(t)$ of position coordinates in space, given as function of time t. This implies that path tracking is achieved by trajectory tracking. Trajectory tracking in this context means that the time frame, including the time when reaching the final state, is fully specified, and a common method is model-based feedforward control combined with online feedback using predefined trajectories.

In contrast, there are many examples where path tracking is possible but trajectory tracking is not, and a typical situation is when an actuator reaches its saturation limit. In all practical systems, there are always limitations on the available control authority, and then the only possibility may be to adjust the speed along the path, or phrased equivalently, to scale the time frame available for completion of the task. As a concrete example, when driving a car and the road exhibits high slip, the only way to stay on the road—*i.e.*, on the desired predefined path—may be to adjust the speed. Further, it is natural, as in the car-driving example, to think in position along the path instead of time: The driver turns at a

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bend (path tracking) not after a certain time (trajectory tracking). In practice this means that the time frame is released, or equivalently phrased, that the speed along the path is adjusted. Nevertheless, there must still be coordination between the degrees of freedom (DoF) of the system to follow the desired path, and early research in this spirit is by means of dynamic scaling of the trajectories [6].

To utilize the freedom of velocity control along the desired path, it is clear that there are two different problems to be solved. One task is to control the traversal along the tangential direction of the path, where the objective typically is some optimal performance, *e.g.*, minimum-time or minimum-energy. The other task is to follow the path, *i.e.*, to coordinate the different DoF of the system such that the desired path is tracked. It is therefore natural to consider both the control of tangential motion along the path and the motion toward the path (along the normal or binormal directions). To this end, we use the concepts $x_{\parallel}$ and $x_{\perp}$, defined more precisely in Section 3, where the main idea is to have largest possible control freedom along the directions of $x_{\parallel}$ together with desired convergence to the path along the directions of $x_{\perp}$.

1.2. Previous research on path tracking

Initial research on time-optimal trajectory generation for path tracking with robot manipulators was presented in [7–11], and extensions with respect to dynamic uncertainties and singular control were proposed in [12,13]. Recently, a convex reformulation of the trajectory-generation problem for time-optimal path-tracking was suggested in [14,15], together with efficient algorithms for computation of the optimal trajectories. Extensions with respect to convex-concave constraints were presented in [16]. Methods for online trajectory generation for time-optimal path tracking were considered in [17,18]. Further application areas for the methods in [15] were investigated in [19].

As stated in the previous subsection, path tracking can be achieved by trajectory tracking, conditioned on that sufficient control authority is available. Within this class of approaches with a given time horizon, there are established algorithms to adjust the control inputs to obtain path tracking in the cases that there is some degree of repetitiveness of the path. Iterative learning control (ILC) is one such successful strategy [20–23]. The typical application scenario of ILC is offline in a batch-oriented structure. Often, ILC methods are limited to tasks where the trajectory is of fixed length, thus not permitting time scaling. Methods for relaxing this requirement in learning were investigated in [24,25]. ILC for optimal path tracking was considered in [26]. Path tracking for mobile platforms was investigated in [27,28]. Feedback linearization for trajectory planning was proposed in [29] and trajectory optimization in constrained environments was considered in [30]. Control laws for path tracking with mobile robots resulting in exponential convergence were proposed in [31]. The major difference between manipulators considered in this paper and mobile robots is the non-holonomic constraints that might be necessary to consider for the latter category of systems.

The present research is a new approach to dynamic scaling of trajectories [6], where the formulation is most related to the previous research in [32]. The algorithm proposed in [32] was formulated as online time scaling of precomputed time-optimal trajectories, but could equivalently be phrased as online velocity control along the path and is here denoted path-velocity control (PVC) [33,34]. Extensions of the PVC algorithm in [32] and alternative approaches to high-accuracy path tracking have later been proposed in, *e.g.*, [35–41], where the extensions mainly are with respect to the constraints on the system that can be accounted for and regarding developments for practical implementations of the algorithms in industrial systems. In particular, important extensions with respect to constraints in the robot workspace were proposed. Dynamic scaling of trajectories for robots with elastic joints was considered in [42], and dynamic time scaling for generating energy-optimal trajectories for robots was proposed in [43]. Another approach to path tracking for position servos with actuator limitations was considered in [44]. Initial research on an alternative formulation of the path-tracking control problem with actuator constraints was presented in [45], where control along the orthogonal directions of the path was introduced and given priority over the control along the tangent of the path, thus not focusing on the coordination of the DoF. Another approach to orbital stabilization for nonholonomic underactuated systems based on transverse linearization, related to the control architecture in this paper, was suggested in [46]. Moreover, a predictive path parametrization for online path tracking was considered in [47], with a similar purpose as the PVC algorithm in [32].

1.3. Contributions

The main contribution of this paper is a complete and integrated control architecture along the lines outlined in Section 1.1 for robust path tracking for robot manipulators with actuator constraints. In the setting of $x_{\perp}$ and $x_{\parallel}$, the control along $x_{\parallel}$ utilizes PVC and builds on previous algorithms for time scaling [6,32], such that if the robot is on the path the controller is equivalent to the algorithm in [32]. In addition, an extension of the controller is introduced that handles fast convergence along the orthogonal directions of the path, $x_{\perp}$, should the robot be off the path. The result is a control architecture that employs coordinated feedback control both along $x_{\perp}$ and $x_{\parallel}$, which is called path-tracking velocity control (PTVC). This strategy, PTVC, achieves robust path tracking for a wide class of mechanical systems and results in a substantial performance increase in the achieved path-tracking accuracy compared to PVC, as demonstrated in Section 7.

1.4. Outline

A motivating example explaining fundamental ideas of the algorithm is presented in Section 2. The natural coordinates of a curve [48,49] is an appropriate framework for defining the tangential direction $x_{\parallel}$ and the orthogonal directions $x_{\perp}$. This is described in Section 3, where also the definition of radius of curvature that is used in the control law is provided. The mechanical systems under consideration are given their mathematical formulation in Section 4. In this section, trajectory generation for such systems is also discussed. Then, based on natural coordinates, the control architecture PTVC with separate terms for tangential and orthogonal control is presented in Section 5. An advantageous property is exponential convergence along the normal directions of the path, and an analysis of convergence properties is presented in Section 6. The complete algorithm is evaluated in Section 7 with extensive simulations on different manipulators. The obtained results, possible extensions, and generalizations of the control architecture are discussed in Section 8, and finally conclusions are drawn in Section 9.

2. A conceptual example

The following example introduces some of the main ideas for obtaining convergence of the path tracking along the transversal directions by creating an inherent attraction to the path, path stability, without hampering the control possibilities tangential to the path, *i.e.*, the path-velocity control.