Abstract

A fundamental problem in robotics is the generation of motion for a task. How to translate a task to a set of movements is a non-trivial problem. The complexity of the task, the capabilities of the robot, and the desired performance, affect all aspects of the trajectory; the sequence of movements, the path, and the course of motion as a function of time. This thesis is about trajectory generation and advances the state of the art in several directions; special attention to trajectories in constrained situations when interaction forces are involved is paid; we bring a control perspective to trajectory generation and propose novel solutions for online trajectory generation with a quick response to sensor inputs; we formulate and find optimal trajectories for various problems, closing the gap between path planning and trajectory generation; the inverse problem of finding the control signal corresponding to a desired trajectory is investigated and we extend the applicability of an existing algorithm to a wider range. Designing trajectories for tasks involving force interaction is difficult, since both the knowledge of the task and the dynamics of the robot are necessary. Alternatively, we can acquire human-generated trajectory. In this thesis, an immersive interface for task demonstration is proposed, where the operator can sense and act through the robot. This is achieved by coupling two robotic systems on a dynamical level. Limitations caused by the singular configurations or the reach of either of the robots are naturally reflected to the other as haptic feedback. We consider a closed-loop approach to trajectory generation for fixed-time problems, where a desired target state (possibly time varying) is achieved by acting upon the feedback from the actual state of a robot. Using the Hamilton-Jacobi-Bellman equation, we derive an optimal controller for the fixed-time trajectory-generation problem with a minimum-jerk cost functional. The controller instantaneously updates the trajectory as a result of changes in the reference signal and/or the robot states. Moreover, a smooth transition between the finite-horizon and an infinite-horizon problem is developed. This enables switching transition between the finite-horizon and an infinite-horizon problem is developed. This enables switching transition between the finite-horizon and an infinite-horizon problem is developed. This enables switching. An analytic solution to the problem of fixed-time trajectory generation with a quadratic cost function under velocity and acceleration constraints is derived. This problem has a wide range of applications in motion planning. The advantage of the analytic solution compared to numerical optimization of the discretized problem is the unlimited resolution of the solution and the efficiency of the calculation, allowing sensor-based replanning and on-line trajectory generation. To extend the idea of closed-loop trajectory generation, by accommodating a more generic form of system dynamics and constraints, we adopt the Model Predictive Control (MPC) framework. We give the interpretation that in the tracking problem the desired output at every sample is specified, while in point-to-point trajectory planning, it is limited to certain samples. This view unifies tracking and point-to-point trajectory generation problems, hence eliminating the need of a separate layer for reference generation. We discuss various choices of models, objective functions, and constraints for generating trajectories to transfer the state of the robot while respecting physical limitations on the motion as well as fulfilling computational real-time requirements. Experiments on an industrial robot in a ball-catching task show the effectiveness of the approach also in demanding scenarios. A rigid-body model of a finger interacting with a trackball is considered. The proposed system and its extension with more fingers are suitable candidates for studying trajectory generation where interaction plays an important role, such as in assembly and manipulation tasks. The trajectory generation algorithm has to handle a number of important features such as unilateral and non-holonomic constraints. Additionally, in this problem task planning, path planning, and trajectory generation are strongly interrelated, which makes using an integrated approach to trajectory generation inevitable. We derive a hybrid, high-index differential-algebraic equation for modeling the system dynamics, which is used for both simulation and finding optimal trajectories. Iterative
Learning Control (ILC) fits into the picture of trajectory generation considering the fact that it finds a proper control signal for obtaining a desired trajectory. We focus on a specific regime of convergence of an ILC algorithm, which is traditionally ignored. We derive frequency-domain criteria for the convergence of linear iterative learning control (ILC) on finite-time intervals that are less restrictive than existing ones in the literature. Additionally, using an example we put forward an idea of how ILC can be adapted for point-to-point trajectory planning.