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Constrained Optimization Path Following of Wheeled Robots in Rough Terrain

Abstract

A system for path tracking of mobile robots which compensates for rough terrain, predictable aspects of vehicle dynamics, and vehicle mobility constraints has been developed, implemented, and tested on the DARPA LAGR platform. Traditional methods for the geometric path following control problem involve trying to meet position constraints at fixed or velocity-dependent lookahead distances using arcs. We have reformulated the problem as an optimal control problem, using a trajectory generator which can meet arbitrary state boundary constraints. The goal state along the target path is chosen dynamically by minimizing a utility function based on corrective trajectory feasibility and cross track error.

1 Introduction

In the context of autonomous vehicles operating in complex environments, precision motion control is both more necessary and harder to do. Modeling errors increase sufficiently in magnitude relative to those in structured indoor environments, that an approach based on improving any amenable aspect of mobility models seems warranted. We present a model predictive, optimal control approach to trajectory following which relies on a capacity to model many aspects of rough terrain vehicle mobility.

1.1 Motivation

Future robotics missions of planetary exploration will require precision motion control for geologic experiments, instrument placement, and infrastructure construction for permanent colonies. Traditional methods of path following fail in challenging outdoor terrain because they do not consider the effects of rough terrain, dynamics, or mobility constraints.

Precision control is also more necessary in complex environments because hazards are both more prevalent and more lethal to the robot. It is harder to do because perception technology presently falls short of adequate prediction of terrain material (traction and compressibility) properties which truly do determine the magnitudes of the external forces that in turn determine how the vehicle responds to its control inputs. Vehicle actuator and body dynamics can also play a significant role in mapping those forces onto vehicle motion.

On the other hand, these effects are not entirely unknown. Without detailed knowledge of terrain shear strength and friction, it is still possible compute estimates of wheel interactions that are much better than no model at all. Steering dynamics and terrain following are also highly predictable in many cases. To the degree that any controller can predict the mean behavior of these random processes, it can reduce the magnitude of the model disturbances and improve path following performance.

1.2 Related Work

Geometric path tracker algorithms for outdoor mobile robots have been part of robotic architectures since the very beginning. Pure pursuit [1] is one of the simplest algorithms for geometric path tracking and is still widely used in robotic applications today. The algorithm is a proportional gain controller that servos on difference between the current heading and the heading to some fixed lookahead point along the path.

Many variations of the pure pursuit algorithm exist today. In [2], the path follower calculates a control based on a combined pure pursuit / proportional-integral-gain controller. Recent work applied to the Rocky series rover platforms at JPL in rough terrain incorporate the effects of the observed slip rate on the heading into the controller [3]. A feedforward approach to minimize total path following error was presented in [4], which increased the lookahead distance proportionally to the heading error and incorporated a dynamic vehicle simulator.

All of these algorithms have advantages and disadvantages. The choice of the lookahead distance in the pure pursuit algorithm can lead to large tracking errors (lookahead distance too large) or instability (lookahead distance too small) if improperly tuned. The feedforward approach can improve the stability of the algorithm, but requires a simulator and only searches a subset of feasible motions. The PID controller is more difficult to tune and incurs large heading when the target path changes abruptly, but is stable.

A robust control tracking method for differentially steered mobile robots was discussed and simulated in [5], where a simplified vehicle dynamics model was used in the control loop to improve tracking performance.

Our approach differs from the prior art in several ways. We have used a real-time trajectory generator which solves for the vehicle-level controls given the initial and terminal state constraints and predictive models of propulsion, suspension, and motion in rough terrain [6][7]. We also choose the lookahead point dynamically based on solving a constrained optimization formulation of an optimal control problem.

1.3 Problem Statement

For a robot with perfect perception, simulation, and control, a path follower would not be required. In reality however, path followers for mobile robots are required to account for unforeseen vehicle dynamics (e.g. wheel slip). We seek to develop a general path follower which could account for predictable errors due to rough terrain and observed vehicle dynamics and automatically selects the optimum from the continuum.

2 Technical Approach

Recent work in continuous primitive trajectory generation for arbitrary vehicle models [6][7] has improved the capacity to generate corrective paths which meet general position, heading, and curvature constraints in rough terrain. The algorithm gains its generality by relying on numerical linearizing and inverting forward models of propulsion, suspension, and motion. This approach can accommodate such affects as rough terrain, actuator dynamics, wheel slip, and any other somewhat predictable effects of interest. It can also accommodate boundary and internal constraints while optimizing an objective function, which might, for example involve such criteria as obstacle avoidance, cost, risk, time, or energy consumption in any combination. An example of a corrective path using this trajectory generation algorithm is shown in Figure 1.

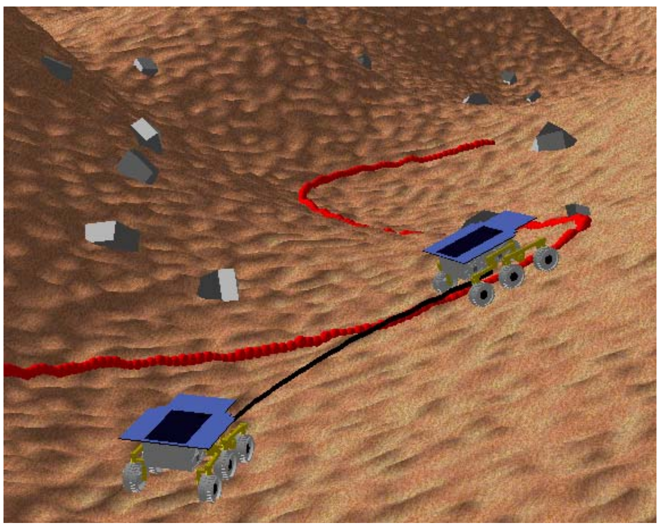

Figure 1: Rough Terrain Trajectory Generator. The trajectory generator, shown here for the Rocky 8 planetary rover vehicle model, can generate a corrective path between boundary states in arbitrary terrain using forward models of propulsion, suspension, and motion for any type of vehicle.

One problem with current tracking algorithms is the choice of the lookahead distance. When the lookahead distance is too long, the path follower will tend to cut corners, while short lookahead distances often result in instability. In effect, choice of the lookahead distance is an embedded optimization problem. The search is one for the correct goal position which minimizes cross track error but results in smooth, stable control. An example situation is shown in Figure 2, where a robot is attempting to reacquire a path. The trajectory generator determines corrective paths to a set of goal states along the target path and chooses an optimum based on minimizing a utility function which penalizes cross track error and high curvatures. Formally, this is a constrained optimization problem. The free variable is lookahead distance, the constraints require that the terminal state lie on the target path, and we look to find the optimal trajectory based on minimizing some cost along the path.

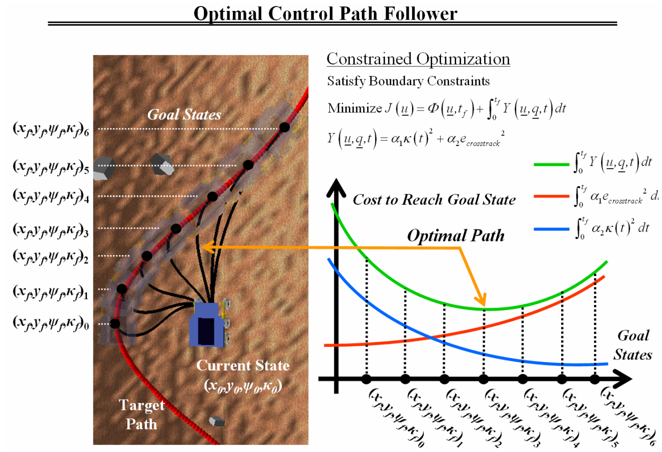

Figure 2: Optimal Control Formulation of a Path Follower. The lookahead distance problem can be reduced to a constrained optimization problem. A search space is generated by using the trajectory generator to a discrete set of waypoints along the geometric path. In general, we want to minimize a utility function (*J*) over the search space. In this example, we look to minimize the integral of squared curvature (smoothness) and the cross track (following) error along the path. After searching the span of possible solutions, an optimal corrective trajectory which minimizes a weighted balance between curvature and cross track error is found

Our path following algorithm relies on two nested control loops, a planning loop and an execution loop. The planning loop determines the proper control based on the current state and a set of goal states along the path (Figure 2). The execution loop (based only actuator feedback) runs at a higher frequency.

3 Experiments & Experimental Snapshots

We have conducted several experiments with our path tracking algorithm on the LAGR (Learning Applied to Ground Robotics) mobile robot platform. The first set of experiments involves trying to follow a geometric path indoors, where most of the vehicle dynamics are predictable.

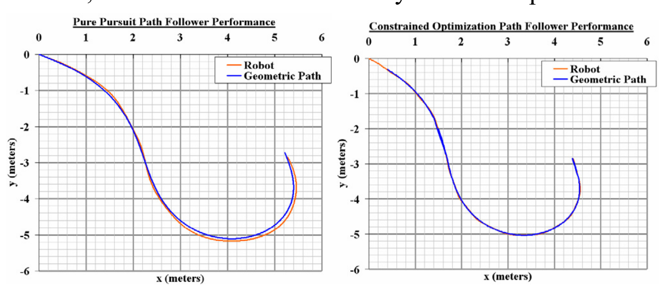

Figure 3: Pure Pursuit vs. Constrained Optimization Path Following Performance. A geometric path was followed using the pure pursuit path follower (left) and the constrained optimization path follower (right) to test performance where vehicle dynamics were predictable. Over a 10 meter long geometric path, the constrained optimization path follower exhibited no more than 1cm of cross track error while the pure pursuit path follower had cross track errors in excess of 10cm.

The experiment showed that the constrained optimization path follower was able to follow the path better than pure pursuit and required no tuning. The constrained optimization path follower performs better because it accounted for heading and curvature constraints in the corrective paths using the aforementioned trajectory generator, and it used a much better model of the vehicle.

The second set of experiments involved path tracking in an environment where vehicle dynamics (e.g. wheel slip) are often unpredictable (Figure 4). Figure 5 shows the path tracking error using the constrained optimization path tracker. Currently we are generating improved vehicle models and better utility functionals for more robust tracking performance in rough terrains.

Figure 4: LAGR Vehicle Path Tracking Experimentation. To test our path tracking algorithm, we ran a LAGR mobile robot platform in a challenging environment where vehicle dynamics are often unpredictable. In this situation, wheel slip is increased by the deep mud.

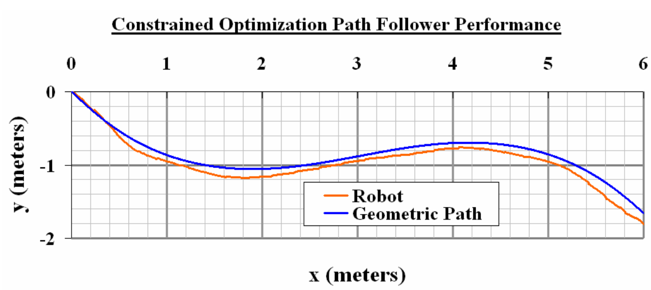

Figure 5: Constrained Optimization Path Following Performance in Outdoor Terrain. First results in path tracking performance in outdoor terrains demonstrate that we have the capacity to follow a geometric path. Improvement of the vehicle dynamics models or better choices of utility functionals will likely lead to better tracking performance.

4 Results

In this paper, we have demonstrated the design and implementation of a control system based on a real-time trajectory generator which provides the predictive component in an optimal controller. Our first set of experiments demonstrated better performance than an implementation of the pure pursuit algorithm in an environment where unpredictable vehicle dynamics are negligible.

The second set of experiments showed that our algorithm remains stable and robust in challenging outdoor environments. In addition to the performance advantages the model predictive approach also requires less tuning than pure pursuit. The lookahead distance is effectively being recomputed every cycle based on an explicit utility criterion and a model of how vehicle behavior changes with speed and terrain shape.

The tracker has been integrated with a rough terrain global planner and both algorithms will be tested on the Rocky 8 rover at JPL in the summer of 2006.

Acknowledgement

This research was conducted at the Robotics Institute of Carnegie Mellon University under contract to NASA/JPL as part of the Mars Technology Program.

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