Abstract

Autonomous vehicles perform time and cost effective operations with minimal or no human effort and hence, have the potential to be used in civilian, commercial and military applications. Pertaining to these applications, the autonomous vehicles often need to travel through waypoints in obstacle cluttered environments. Path planning plays a major role in the mobility of autonomous vehicles by generating obstacle-free paths through given waypoints. Of particular interest is path planning for nonholonomic vehicles such as cars and bank-to-turn UAVs. These nonholonomic vehicles have limited turn rate capability which directly imposes constraints on the curvature of the path. This thesis proposes a new Four Parameter Logistic (4PL) curve based Continuous-Curvature (CC) path planning methodology for nonholonomic vehicles.

Four Parameter Logistic curve is used as a regression assay tool in Biology and Medicine. The first part of the thesis introduces and analyzes the 4PL curve as a smooth path planning tool with control over its shape using an explicit equation and two design parameters. Joining two consecutive waypoints, S and half-S-shaped paths are derived from the 4PL curve. It is proven that the 4PL paths have continuous curvature together with zero curvature at both the ends. Further, to satisfy the vehicle maximum turn rate constraint, a conservative upper bound is obtained for the maximum curvature of the 4PL paths. In addition, confinement regions of the 4PL paths are deduced.

Obstacle avoidance characteristics of the 4PL paths are analyzed in the next part of the thesis. Local axis-aligned rectangular and circular obstacles are considered and closed-form conditions on the two design parameters are derived for avoiding them. Conditions for path generation, maximum curvature bound, and obstacle avoidance are analyzed in 2-D design parameter space, and their intersection region is defined as a solution set. The solution set approach provides multiple feasible paths connecting two waypoints and hence, reduces the computation cost for planning.

The next part of the thesis further develops the obstacle avoidance analysis for realistic obstacles modeled as convex polygons. Closed-form conditions on the two design parameters are derived as sufficient conditions for obstacle avoidance. This obstacle avoidance analysis is incorporated in the solution set approach and applied to a UAV path planning problem with airspace restrictions. Airspace restrictions (no-fly zones and airspace) are modeled as convex polygon and feasible set of waypoints and respective headings are selected from the generalized Voronoi diagram. Using the solution set approach, feasible 4PL paths are generated between each pair of consecutive waypoints, and joined with heading and curvature continuity. The proposed path planning approach is extended to 3-D scenarios where solid polyhedron obstacles are considered together with a linear UAV altitude variation. The proposed path planning approach is combined with a nonlinear path following algorithm and implemented on a high fidelity Six Degree-of-Freedom (6-DoF) UAV model.

Next, the problem of smooth path planning for passages with curvature and heading discontinuities is considered. This problem arises when an autonomous vehicle traverses between prescribed boundaries such as corridors, tunnels, channels, etc. Generation and confinement of CC paths inside the passages are the key challenges in this problem. For passages with curvature discontinuities, CC half-S-shaped 4PL paths are generated in each passage segment and joined with heading and curvature continuity. Further, confinement constraints also result in closed-form conditions on the two design parameters. For passages with heading discontinuities, the half-S-shaped paths are used to join midlines of two consecutive passage segments and passage confinement is guaranteed by varying the path ends on the midlines. Various passages with curvature and heading discontinuities are considered to present the viability of the proposed solution.

The last part of the thesis proposes a smooth maneuver planner for parallel parking a realistic size car-like vehicle in a single trial. The proposed approach also addresses the maneuver replanning issue where the vehicle start position may vary because of vehicle dynamics or *modeling uncertainties. The parking problem is formulated in a point-to-ray framework where the point and the ray correspond to the parking position and starting position locus, respectively. Inherent free end of the 4PL curve provides a natural solution to this variable end maneuver planning problem. The solution methodology relies on a modified configuration space approach which considers vehicle dimensions and all collision possibilities. The maneuver planning approach is implemented on a double-track Ackerman steering vehicle model.*

The thesis also includes a detailed comparison with existing smooth curves (namely, Bézier curve, splines, and clothoid) based path planning methods. In contrast to the recursive (Bézier curve and splines) and numerical (clothoid) path computation methods, the proposed curve generates multiple CC paths using a closed-form explicit expression and just two design parameters. Moreover, curvature continuity with zero end curvature provides inherent scalability to the proposed approach. Another significant advantage is the simple closed-form conditions for avoiding obstacles lying inside the confinement region, where the Bézier curve and B-spline based approaches require iterative and numerical solutions.