SUPERVISORY CONTROL OF UNCERTAIN UNDERACTUATED VEHICLES

(EXTENDED ABSTRACT)

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The study of underactuated vehicles, *i.e.*, systems with fewer actuators than degrees-of-freedom is motivated by the fact that it is usually costly and often not even practical to fully actuate autonomous vehicles due to weight, reliability, complexity, and efficiency considerations. Typical examples of underactuated systems include robotic manipulators, wheeled robots, walking robots, spacecraft, aircraft, helicopters, missiles, surface vessels, and underwater vehicles. From the point of view of the controller designer, the tracking problem, which is concerned with the design of control laws that force a vehicle to reach and follow a time parameterized reference (*i.e.*, a geometric path with an associated timing law) is especially challenging. This is because most of these systems are not fully feedback linearizable and exhibit nonholonomic constraints, therefore standard tools used to control nonlinear systems—such as feedback linearization and integrator backstepping—are not directly applicable. The reader is refereed to [1] for a survey of these concepts and [2] for a framework to study the controllability and the design of motion algorithms for underactuated Lagrangian systems on Lie groups.

The classical approach for trajectory tracking of underactuated vehicles utilizes local linearization and decoupling of the multi-variable model to steer the same number of degrees of freedom as the number of available control inputs, which can be done using standard linear (or nonlinear) control methods. Alternative approaches include the linearization of the vehicle error dynamics about trajectories that lead to a time-invariant linear system (also known as trimming trajectories) combined with gain scheduling and/or Linear Parameter Varying (LPV) design methodologies [3, 4, 5, 6]. The basic limitation of these approaches is that stability is only guaranteed in a neighborhood of the selected operating points. Moreover, performance can suffer significantly when the vehicle executes maneuvers that emphasize its nonlinearity and cross-couplings.

Nonlinear Lyapunov-based designs can overcome some of the limitations mentioned above. Several examples of nonlinear trajectory tracking controllers for marine underactuated vehicles have been reported in the literature [7, 8, 9, 10, 11, 12, 13, 14, 15].

Typically, tracking problems for autonomous vehicles are solved by designing control laws that make the vehicles track pre-specified feasible "state-space" trajectories, *i.e.*, trajectories that specify the time evolution of linear and angular positions and velocities that are consistent with the vehicles' dynamics (*e.g.* [8, 16, 17, 10, 12, 13, 14, 15]). This approach suffers from the drawback that usually the vehicles' dynamics exhibit complex nonlinear terms and significant uncertainty, which make the task of computing a feasible trajectory hard. Fortunately, in practical applications one often only needs to track the desired position making it possible to bypass the computation of feasible state-space trajectories.

It is relevant to point out that most of all the approaches described above only solve the problem in the horizontal plane. Only a few authors have tackled this control problems in three dimensional space. The reason might be the fact that the vehicle's dynamics are by far more complex, the number of degree of freedom which are not directly actuated, typically, increases, and therefore the control design is much more involved. For example, for an underactuated underwater vehicle, the dynamics include sway and heave velocities that generate nonzero angles of sideslip and attack, which must be necessarily be taken into account during the controller design phase.

Motivated by the above considerations, in [18] we proposed a solution to the position tracking problem for a fairly general class of underactuated autonomous vehicles that is applicable to motion in either two or three dimensional spaces. The tracking controller proposed yields global stability and exponential convergence of the position tracking error to

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a neighborhood of the origin that can be made arbitrarily small. The desired trajectory does not need to be a trimming trajectory and can be any sufficiently smooth time-varying bounded curve, including the degenerate case of a constant trajectory (set-point). The control algorithm builds on iterative Lyapunov-based techniques, in particular, integrator backstepping [19, 20]. This is an important issue, since the availability of a Lyapunov function suits the need of robust control designs in the presence of noise measurements, bounded disturbances, and unmeasured thruster dynamics [12].

In this work, we demonstrate how the techniques of supervisory control combined with the design procedure outlined in [18] can be applied to construct a hybrid feedback control law that drives the position error to a small neighborhood of the origin in the presence of possible large parametric modeling uncertainty. The basic idea behind supervisory control [21, 22, 23, 24, 25, 26] is to employ logic-based switching among a suitable defined family of candidate controllers. Each one of these controllers is designed for an admissible nominal model of the plant, and the task of the supervision logic is to orchestrate the switching among the candidate controllers by deciding, at each instant of time, the candidate feedback controller that is more adequate. In order to guarantee stability and avoid chattering, a form of hysteresis is employed in the switching logic. In [24], logic-based switching control laws were derived to park a nonholonomic wheeled mobile robot with parameter uncertainty. Another application of supervisory control is described in [25] for the control of induction motors with uncertainty in the rotor resistance.

A distinct class of motion control problems associated with autonomous vehicles is *path following*. In path following, the vehicle is required to converge to and follow a path that is specified without a temporal law. [27, 28, 29, 30, 31]. Pioneering work in this area for wheeled mobile robots is described in [27, 28]. In [30], Samson addressed the path-following problem for a car pulling several trailers. More recently, Altafini [32] describes a path following controller for a n trailer vehicle that provides local asymptotic stability for a given path of nonconstant curvature. Path following systems for aircraft and marine vehicles have been reported in [33, 4, 34, 35, 36]. The underlying assumption in path following control is that the vehicle's forward speed tracks a desired speed profile, while the controller acts on the vehicle orientation to drive it to the path. Typically, in path following controllers, smoother convergence to a path is achieved and the control signals are less likely pushed to saturation, when compared to trajectory tracking controllers [33, 34]. Recently, using the approach suggested in [33], an output maneuvering controller was proposed in [37] for a class of strict feedback nonlinear systems and applied to maneuver fully actuated ships.

Using the same ideas, we can re-design the tracking controller in order to solve the maneuvering problem. Following the approach of [37], the desired behavior of the plant in the output space is separated into two subproblems: *i)* converging to and following a desired parameterized path, denoted as a geometric task, and *ii)* satisfying a desired dynamic behavior along the path, denoted as a dynamic assignment task.

Future research will address the control of underactuated vehicles with noise and in the presence of disturbances. Typical disturbances for marine vehicles include the ones induced by wave, wind, and ocean current.

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