Introduction and Conclusions

Nonlinear control of underactuated non-holonomic marine vehicles.

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Contents

CHAPTER 1 INTRODUCTION, OBJECTIVES AND STRUCTURE. 7

1.1. INTRODUCTION. 7
1.2. OBJECTIVES OF THIS THESIS. 8
1.3. STRUCTURE OF THE PHD DISSERTATION. 9

CHAPTER 2 CONCLUSIONS. 11

2.1. CONCLUSIONS 11
2.2. FUTURE WORK. 12

Chapter 1 Introduction, Objectives and Structure.

1.1. Introduction.

Most of the vehicles used for marine, terrestrial and aerial transport are underactuated. In general this kind of vehicles are more efficient, simple and inexpensive that the fully actuated ones. Only in a few cases were a high maneuverability and performance is needed, the cost of fully actuate vehicles is justified.

Usually the vehicles employed on maritime industry are surface vessels. In general this vehicles are equipped with a propeller and a rudder that allows to control its velocity and orientation, making the control problem a challenge with many practical applications (Fossen, 2002).

From the point of view of Automatic Control, the underactuated vehicles have nonholonomic restrictions that make the control design more complex. Their dynamics are highly nonlinear involving advanced controllability concepts (Hermann & Krener, 1977; Megretski, 2003). This challenging problem defines an active research topic that continue producing interesting results nowadays (Kai, Kimura & Hara, 2005).

The maneuverability of this vehicles is limited by second order nonholonomic constraints, that make the design of control laws high dependent of the specific control problem that must be solved. A complete classification of these problems can be found on (Olfati-Saber, 2001).

While some trajectories can be followed by means of smooth and time independent control laws, this is not possible when the objective is to stabilize the vehicle in a desired point with a desired orientation. This problem is known as point stabilization or dynamic positioning and due to the famous inexistency result (Brockett, 1983) this problem is really hard to solve.

In general each control problem about underactuated vehicles is solved separately, giving a different control law for each control problem (Aguiar & Hespanha, 2003; Aguiar & Pascoal, 2002; Pettersen & Nijmeijer, 2001; Pettersen & Egeland, 1996; Sira-Ramírez & Ibañez, 2000). However some authors try to solve more than one problem with the same control law such as (Aguiar & PHespanha, 2007; Do, Jiang & Pang, 2002; Encarnação & Pascoal, 2001).

The main difference between underactuated maritime and terrestrial vehicles is that the first ones have a drift velocity that is not negligible. This vehicles can not be transformed into a driftless form. The constraint on their movement is second order nonholomimic because it involves accelerations and not only velocities, as happens with terrestrial vehicles (which have only first order nonlolomonic restrictions).

There are many authors that used the hovercraft as a representative case of study as the main problem with this vehicles is the drift and the Hovercraft have a drift velocity that is comparable to its surge velocity (Aguiar, Cremean & Hespanha, 2003; Dumbar, Olfati-Saber & Murray, 2003; Fantoni, Lozano, Mazenc & Pettersen, 2000; Seguchi Hiroaki, 2003; Sira-Ramírez & Ibañez, 2000).

Moreover there exist international frameworks that use Hovercrafts as a model of underactuated vehicles. It must be highlighted the MVWT platform developed in Caltech, the experimental setup used in (Seguchi & Ohtsuka, 2002) or the multiple Hovercraft laboratory of (Vladimerou et al., 2004). The aim of these platforms is to dispose of a benchmark to test the control laws developed for underactuated autonomous vehicles.

In this PhD Thesis the same approach is followed. An experimental setup that uses the Hovercraft as a model of nonholomonic, underactuated and nonlinear vehicle has been developed and some control strategies for this vehicle were developed and tested.

1.2. Objectives of this Thesis.

This Thesis is dedicated to the control problems of underactuated surface vessels. The model proposed in this dissertation is a hovercraft that is described on detail on Chapter 3 of the dissertation.

The aim of this work is the design of control laws to solve the trajectory tracking and point stabilization problems. This control laws must deal with limitations on the control actions and the vehicle constraints. In order to solve these problems the following objectives are defined:

I. Study the controllability of the Hovercraft in order to establish the kind of problems that can be solved and the physical limitations of the vehicle.

II. Implement an experimental platform that could be used as testbed to validate the control laws developed on this Thesis.

III. Obtain and validate a model of the system for simulating the Hovercraft and for the design and analysis of the control laws.

IV. Solve the Point Stabilization problem taking into account that the control signals allowed on the real system are three valuated ones (throttle, nothing, and reverse throttle).

V. Solve the Tracking problem of the Hovercraft considering continuous control actions.

VI. Solve the Tracking problem using only the three valuated control inputs allowed on the experimental setup.

VII. Demonstrate theoretically the stability of the proposed control laws on presence of noise, disturbances and parametric model uncertainties.

VIII. Validate experimentally the designed control laws that use three valuated control actions (and hence are directly applicable on the experimental setup).

1.3. Structure of the PhD Dissertation.

This dissertation is organized in seven chapters to be sequentially read. However chapters 2 to 6 of the dissertation contain a little introduction of the problem to be solved as well as a discussion of the results obtained in order to make each chapter self contented.

Chapter 2:

In this chapter the general structure of the Hovercraft model is presented. This model will be used on the rest of the dissertation. Afterwards the nonholonomic restriction of the Hovercraft will be studied with great detail, paying a special attention to how it affects to the trajectories that can be followed. Moreover local and global controllability of the state will be studied. Controllability around trajectories and Brockett theorem limitations on control laws will be deeply analyzed too.

Chapter 3:

This chapter explains the implementation of the laboratory system. The physical implementation (hardware setup) and the computer programs developed in order to control the Hovercraft (software architecture) are described. The LabVIEW blocks that compose the software implementation are analyzed in depth describing the problems they solve (computer vision, control law evaluation, communications with the vessel and graphical user interface). Finally the platform is used to obtain and validate the parameters of the Hovercraft model.

Chapter 4:

In this chapter a control law that solves the Point Stabilization problem is developed. This control law is discomposed in two parts. The first one tries to stabilize the transversal dynamics of the vehicle using the torque generated by the differential drive of the two thrusters. The second one uses the total force to bound the longitudinal dynamics by some hysteresis. Finally both control laws are unified by a proper selection of the hysteresis in order to make both dynamics converging at the same time. Stability is demonstrated theoretically and tested both in simulation and experimentally.

Chapter 5:

This chapter solves the trajectory tracking control by using a smooth control law. First a study of the kind of trajectories is presented. then a characterization of the trajectories that can be followed using only local information about the trajectory (well defined trajectories) has been done. Afterwards a control law that is capable to converge from any initial condition to any well defined trajectory by using bounded continuous control actions on the actuators has been developed. Its stability has been mathematically demonstrated and also the performance of the control law is analyzed on simulation.

Chapter 6:

This chapter is dedicated to the trajectory tracking control of an underactuater hovercraft by using only a discrete set of control inputs (maximum acceleration, no force and maximum reverse acceleration in each motor). First a subset of the well defined trajectories is defined such as the discrete control actions can dominate over the continuous forces needed to track the trajectory. Then a control law that employs only discrete control inputs is designed in order to track any trajectory on this subset starting from any bounded initial condition. Semi global stability has been demonstrated theoretically showing also that the region of attraction of the system can be made arbitrary big. Finally the control law is tested in simulation and with the experimental setup.

Chapter 7:

Finally the conclusions of this Thesis are showed highlighting the original results obtained. Also new research topics that are open in this Thesis are presented as future work.

Chapter 2 Conclusions.

In this chapter main conclusions of the PhD dissertation and future work are presented.

2.1. Conclusions.

This Thesis makes a deep study about the control problems that can be solved on an underactuated hovercraft. Results about local and global controllability of the state has been obtained by means of direct methods. Moreover the conditions that a trajectory must satisfy in order to allow a hovercraft to be controlled has been studied. This results complete a previous study developed in (Fantoni et al., 2000). This gives an exhaustive analysis of what can be done with an underactuated Hovercraft.

With the purpose of validating the control laws designed on this PhD, the experimental setup consisting on a radio-controlled Hovercraft, and a computer vision system has been developed. Furthermore a set of libraries in LabVIEW that solve the computer vision problem, calibration of the system, communication with the vehicle and control implementation have been developed. With this system the parameters of the model were experimentally obtained and validated. This model has been used in the simulations and the control law design.

Moreover the Point Stabilization problem has been solved by using a discrete set of control inputs. Stability analysis of the longitudinal and transversal dynamics was carried out by using nonlinear analysis tools.

In addition, a new strategy to analyze switching systems without a common Lyapunov function has been developed. This method is based on the *equivalent system* concept. Employing this new tool the global convergence of the point Stabilization controller has been demonstrated.

A new continuous control law has been designed in order to follow any time parameterized well defined spatial trajectory. This control law solves the problem of actuator saturation by generating control signals that are bounded for any initial condition. A proper selection of the control action bounds guarantee that the control actions generated by this law will be always applicable on the real system. The stability of this control law has been demonstrated theoretically and its performance has been tested on simulations.

Also a new control law for the trajectory tracking problem has been developed employing discrete control actions (maximum throttle, nothing and maximum brake). In order to guarantee the stability theoretically is necessary to restrict the trajectories to a subset of the well defined trajectories. In this subset the discrete set of control actions available are enough to exactly follow the trajectory.

This means that for any trajectory on this subset it is always possible to obtain forces and torques of any desired sign such that their modulus are greater than the force and torque needed in any time. Under these conditions it was possible to show semi-global stability, where the region of convergence could be made as big as necessary by a proper selection of the controller constants. This control law has been tested with experiments with the real hovercraft.

For all the proposed designs a deep analysis of the effect of noise, disturbances and parameter uncertainty has been done. It has been demonstrated that for all the control designs there exists some robustness margin such as if noise, disturbances and uncertainty are below this margin practical stability is achieved (The system is finally bounded by a small bound that depends on disturbances and noise).

Finally it can be concluded that all the objectives presented on the introduction has been accomplished.

2.2. Future work.

This PhD thesis opens new research lines that are proposed as future work. This future work includes new theoretical studies about control laws and practical improvements on the experimental setup.

First from a practical point of view it will be very interesting to extend the experimental setup to manage multiple vehicles. Another interesting enhance consists on allow thrusters to produce continuous control actions. This extended setup can be used as a experimental framework for testing collaborative strategies.

The parameters of the model are time varying. So in order to achieve better performance adaptive control laws should be studied. This could make the system more robust against parameter changes, adapting the control parameters to the configuration or the real system (battery level, mass distribution,...)

On chapter 6 semi global stability has been demonstrated for the trajectory tracking control law even though simulation results shows that the control law achieves global asymptotic stability.

Moreover restrictions imposed on the trajectory are so conservative. This suggests that a more precise description of the trajectories that can be followed by this control law could be obtained using analysis techniques based on averaging.

Finally the last line of future work consists on solving the problem of path following. In general a control law designed for tracking can be easily adapted to be a a Path Following control law (defining the reference velocity as a function of the position and then computing the position of a “*rabbit*” over the path can be tracked by the previous control laws). However a deep analysis of the concrete problem is needed in order to obtain a path following control law that exploit the structure of the problem.

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