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Intelligent rudder control of an unmanned surface vessel

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ABSTRACT

Trajectory tracking control for unmanned marine surface vessels (USV) is quite complex because of the strongly non-linearity of the system and the presence of uncertainties and environmental changing conditions. To face those issues, in this paper intelligent and conventional strategies are used as the main control framework for the rudder angle of an USV. The guidance law calculates the desired angle and estimates the trajectory based on the dynamic model of the autonomous ship, which has been generated from real data obtained from experiments with a scale prototype. The model accounts for the physical limitations of both the rudder and the ship propulsion system. An adaptive control law is first proposed which is suitable for any different trajectory and can deal with varying path shapes. This gain scheduling approach utilizes PID controllers whose tuning parameters have been optimized by genetic algorithms (GA) for the different operation points (GS-PID-GA). Besides, a fuzzy logic controller (FLC) is designed to deal with the uncertainties of the dynamics and to include the expertise of an operator. Simulations validate the effectiveness of the proposed control approaches that have been compared with conventional control.

1. Introduction

Automatic control systems are currently an interesting issue within marine applications (Martin, 2013). In recent years, the research has expanded from control of manned vessels to also include unmanned vessels. Autonomous Surface Vessels (ASV) or Unmanned Surface Vehicles (USV) is with increasing popularity being seen in various applications. The rising need for transportation services and the demand for a higher safety level have been the driving forces for a general trend towards path following control of marine vehicle systems (Roberts, 2008). There are several scenarios where autonomous ships can be used: search and rescue, spill collection, surveillance, placing nets, bathymetric map creation, transportation, exploration tasks, environmental monitoring, marine survey, coastal and inland monitoring, etc., (Cruz de la, Aranda, & Girón, 2012).

Motivated by the interest in reducing human intervention in dangerous environments, as well as achieving a more accurate and efficient control, ship controllers have gone through a technological evolution, from classical Proportional-Integral-Derivative (PID) controllers to a more sophisticated robust and adaptive control, where artificial intelligence techniques play an important role (Santos, 2011).

However, the control of surface vessels is still a very challenging problem. Surface marine vehicles can become unsteady and quite difficult to control. When dealing with surface vessels in general, uncertain nonlinear hydrodynamics and external disturbances must be considered. Its complexity is in part due to the non-linear dynamics and strong couplings between the multiple state variables (Fossen, 2002). These aspects make quite complicated the obtaining of a mathematical model, which represents the dynamics with an analytical approach. That is why traditional control systems may not have a good performance with these complex nonlinear multiple-input-multiple-output systems. Even sophisticated conventional control solutions are usually based on linear analytical models, which are not the best representation of this type of real marine vehicles (Sharma, Sutton, Motwani, & Annamalai, 2014). Even more, it is necessary to deal with the uncertainty that comes from the system itself and the varying environmental conditions (Sonnenburg & Woolsey, 2013).

Nevertheless, artificial intelligent techniques can be very useful for ship autopilots and course guiding. Intelligent controllers have proven very efficient to deal with nonlinearities and uncertainties that appear in marine applications (Santos, 2014).

On the one hand, fuzzy logic-based systems have proven to be a good alternative for nonlinear system, as it is the case of USV. Fuzzy Logic Controllers (FLC) are non-linear controllers that also

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incorporate the expertise of an operator. For USV, this intuitive knowledge is available.

On the other hand, marine systems are in changing environments, and its own dynamics varies depending on environmental conditions. A general control law may not be the best one for these systems if it is not enough robust. In this sense adaptive control law, and particularly gain scheduling strategy, is a good choice to address these systems that vary their behavior depending on the operating point.

Therefore in this paper we have implemented these advanced approaches for unmanned vessel control, showing their efficiency. Our work is focused on the control of the vehicle dynamics via actuator inputs to complete certain missions (path following).

The first trajectory tracking proposal is the design of a fuzzy logic controller that calculates the rudder angle of the ship according to the desired course angle. As it is well known, fuzzy logic provides with a heuristic (not necessarily model-based) approach to nonlinear controller generation and deals with the uncertainty that comes from the environment. Besides, the FLC is simple to design. It can incorporate the knowledge of an expert, which in the case of trajectory tracking is very intuitive. In addition, being a non-linear control it allows to deal with realistic characteristic such as actuator saturation, which makes the system nonlinear.

The second path following proposal is an adaptive control law, a gain scheduling PID controller optimized by Genetic Algorithm (GS-PID-GA). The proposed GS-PID-GA control relies on several points. On the one hand, the field of marine vehicles has a long tradition of applying conventional control theory, which provides robustness to the control. This makes users comfortable working with PID regulators, of which there is a long experience in control. Indeed, conventional controllers are still a good solution for an automatic steering system which is a typical single-input-single-output case, but not sufficient for complex and strong coupled non-linear MIMO systems such as USV (Zheng, Negenborn, & Lodewijks, 2014). On the other hand, gain scheduling adapts the control law to the changes of the operating conditions of the system. The scheduling variable we have selected –the trajectory- is general enough to be applied in different environments: in lakes and sea, for different surge speeds, for different size and shape of ships, etc. We think that the choice of this scheduling variable makes the tracking more effective than other papers which present a more specific solution (Liu, Yuan, & Zhang, 2015; Zhixiang et al., 2015). Finally in this proposal we have applied genetic algorithms to tune the controllers. Genetic algorithms perform an evolution-based stochastic search that can be useful in finding good solutions to practical complex optimization problems, in our case to the tuning of the adaptive control law. Thus we are optimizing the control for different operating conditions.

Therefore, the key contributions of the present paper are twofold: (i) to introduce intelligent controllers in conventional control structures, and (ii) to propose a synergy that makes them more efficient for trajectory tracking of unmanned surface vessels. The intelligent and advanced approaches have proved interesting for USV path following, not only when applied separately but also in combination with conventional control strategies.

The USV trajectory tracking control strategies have been compared in terms of characteristics of the marine system response, as overshoot, steady state error and settling time. The advanced and intelligent controllers give better results than the conventional one. This is very convenient as an accurate trajectory tracking avoids obstacles and prevent accidents. On the other hand, they require less control effort, resulting in a better conservation of the actuators and a longer life time.

The USV used for experimental testing is a 1/15 scale model of an operational autonomous vessel. These experiments have provided a model from the real data and allow us to test the different controllers on it.

The rest of this paper is organized as follows. The following section summarizes the related works on this topic found in the literature. The marine system is described in Section 3. The modeling and the characteristics of the replica of the ship are presented. A gain scheduling PID control strategy which has been tuned by genetic algorithms is developed in Section 4. An intelligent control based on fuzzy logic is designed and applied to the marine craft in Section 5. In Section 6 simulation results are shown and comparison between control laws is discussed. Conclusions end the paper.

2. Related works

In this section we present the literature on course control of Unmanned Surface Vessel (USV) and our main contributions regarding these works.

Along the large history of the marine systems, different control strategies have been applied to the design of ship autopilots. Sperry and Minorski developed the first autopilot in 1922 and led to the introduction of the proportional-integral-derivative (PID) controller for automatic ship steering. Since then, the simple conventional regulator and much more sophisticated controllers have been applied to marine crafts. From the first adaptive autopilot introduced by Amerongen, Udink, and Cate (1975), to the application of backsteeping techniques that guarantee the convergence of direction and position in relation to a reference trajectory (Do, 2010; Dong, Wan, Li, Liu, & Zhang, 2015), or exploit the sliding mode control (Conte, Capua, & Scaradozzi, 2016). But most of these sophisticated control algorithms have the disadvantage of requiring high computational effort (Pan, Lai, Yang, & Wu, 2015).

Although intrinsically marine vehicles are known to exhibit non-linear dynamic characteristics, modern marine autopilot system designs continue to be developed based on both analytic linear and non-linear models. The book by Fossen (2011) collects results on control of marine crafts. It is mainly focused on feedback control methods such as PID controllers and more advance motion control strategies based on optimal control theory. SISO and MIMO PID control is applied to a nonlinear 3 degrees-of-freedom (DOF) and 6-DOF models of the marine vehicle. The interest this book has caused shows that conventional control is still widely applied to marine surface vessels. That is, classical control is an indispensable reference. That is why in our work we have compared our control proposals with a PID controller. Besides, in order to make a fair comparison, we have optimized the tuning parameters of the conventional controller by applying genetic algorithms in order to achieve its best performance.

Even more, PID control is still being applied to USV. In the paper presented by Guo, Wang, and Dun (2015), the main control system consists of PID controllers in the inner and outer loops. The unmanned ship has conducted a lake test with satisfactory results. Xu (2014) claims that PID controller is used in most of the course-keeping closed-loop control of unmanned surface vehicles. Xu and Soares (2015, 2016) present an optimized two-dimensional path following algorithm used for way-points tracking of a surface ship. In both papers a PID heading autopilot is used for the ship control.

However, the parameters of the PID regulator may be difficult to tuning. In the literature the application of Genetic Algorithms (GA) and other evolutive techniques to the optimization of the tuning parameters of conventional controllers can be found. The following works can be taken as examples, among others. By Yu, Liu, Liu, and Wang (2015), a self-tuning PID controller for fin/rudder roll stabilization is optimized using multi-objective genetic algorithm. In this paper the performance index to be optimized includes the energy. They also compare the proposal with traditional control to