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Research article

Dynamic surface fault tolerant control for underwater remotely operated vehicles

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ABSTRACT

In this paper, we present a two stages actuator Fault Tolerant Control (FTC) strategy for the trajectory tracking of a Remotely Operated Vehicle (ROV). Dynamic Surface Control (DSC) is used to generate the moment and forces required by the vehicle to perform the desired motion. In the second stage of the control system, a fault tolerant thruster allocation policy is employed to distribute moment and forces among the thrusters. Exhaustive simulations have been carried out in order to compare the performance of the proposed solution with respect to different control techniques (i.e., PID, backstepping and sliding mode approaches). Saturations, actuator dynamics, sensor noises and time discretization are considered, in fault-free and faulty conditions. Furthermore, in order to provide a fair and exhaustive comparison of the control techniques, the same meta-heuristic approach, namely Artificial Bee Colony algorithm (ABC), has been employed to tune the controllers parameters.

1. Introduction

Since the '50s Remotely Operated Vehicles (ROVs) are exploited for military purposes, especially by the U.S. and U.K. navies, due to their capabilities to recover mines, torpedoes and even nuclear devices [1]. Nowadays, ROVs are also used in a wide range of civil operations, e.g., monitoring of submarine oil plants [2], dams [3] and inspection of wrecks and submarines [4]. A ROV for heavy works, which can dive for thousands of meters, is considered in this work, namely a ROV used by SNAMprogetti (Fano, Italy) in the exploitation of combustible gas deposits at great water depths [5]. Our objective is to design a control law for the tracking problem with actuation fault tolerant capabilities, which is a key feature to increase autonomy and reliability, despite the required task.

Many control laws have been proposed in the literature in order to intrinsically obtain robust and fault tolerant control, while demanding a limited control effort at the same time. Most of the nonlinear controllers known in literature aim to cancel the nonlinearities of the plant, by imposing a desired stabilizing (linear) dynamics. These cancellations are obtained via control input: each technique differs from the others in the way this objective is achieved. In particular, when the derivative of some functions are involved in the process, the problem of "explosion of terms" may occur: this is the case of backstepping control, where the i-th state variable is controlled via the $(i+1)$-th state variable [6]. The chain of controlled variables requires the calculation of higher order derivatives, hence, the control law can become very complicated as the mathematical model grows in size and complexity. To overcome this problem, a Dynamic Surface Control (DSC) has been proposed in Ref. [7]: DSC technique can be seen as a modified version of the backstepping technique that exploits low pass filtering. The filtered signals are calculated at each step from internal control signals, and then they are used in the control law in order to replace analytical differentiation, hence solving the explosion of terms problem. The two control laws are different, and each one has a theoretical background which establishes the parameters domain to ensure stabilization and tracking. Hence, the DSC leads to simpler control laws and lower computational complexity; in addition, it provides high frequency noise filtering and makes the state-space variables to change smoothly, avoiding sudden bumps that can be generated by noises, disturbances or a steep reference.

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Many other contributions have been proposed in the literature. In Ref. [7], Single Input-Single Output (SISO) systems with model uncertainties are considered. In Ref. [8], a neural network adaptive DSC is presented, while in Ref. [9] an adaptive dynamic surface control of a system with unknown dead zone is considered. In Refs. [10,11], the authors present the interesting extension of the DSC to Multi Input-Multi Output (MIMO) systems. The control law presented in this paper is based on DSC, and the control architecture is modified in order to cope with faults.

Several techniques have been developed to cope with actuator faults, such as in Refs. [12–14]. Some recent papers investigate different solutions to overcome the presence of faults and/or disturbances: a possible approach is the realization of robust control laws, as sliding mode control [5,15,16]; another method is based on active fault tolerance, which exploits the knowledge given by a Fault Detection and Diagnosis (FDD) module [17–20] in order to cope with the presence of faults [21]. In order to attain the tolerance against actuator faults, a control allocation algorithm, based on the modified Moore-Penrose pseudo-inverse, is introduced in this paper. It provides to distribute the effort of the virtual inputs to the available thrusters, and it represents one of the most exploited fields of control [22] because it greatly simplifies the synthesis of the control laws. Since the '80, the control allocation has been studied; the approach proposed in this paper consists of a weighted version of the pseudo-inverse based method [23].

A large number of works about ROV control are proposed in the literature. The most viable approach is to design linear control laws, like PID controllers, eventually associated with a linearization of the model. Anyway, in the past years, a lot of studies about ROVs mathematical model were made, hence, the model based technique represents a common approach. The most popular applied nonlinear techniques are sliding mode [5,15] and backstepping [24]. DSC has also been applied for the control of underwater vehicles, as in Ref. [25]. In particular, a DSC control law for a ROV system is proposed in Ref. [26], however, the stability of the closed-loop is not discussed, and fault tolerance is not considered. Nonlinear model based control techniques generally require the tuning of different parameters. Due to the large number of parameters, the presence of unmodeled dynamics, time delays and nonlinearities of real systems, tuning is challenging and cannot be solved in analytical way. To overcome this problem, a recent heuristic random search algorithm is adopted in this paper, namely the Artificial Bee Colony (ABC) [27]. The advantages of this algorithm lie on its small number of parameters to be set, and on the convergence speed towards sub-optimal solutions.

The main contribution of this paper is to develop a Dynamic Surface Control law for the trajectory tracking of a ROV, described by a fully detailed mathematical model, where the main dynamics are independently dealt, and thus the cross-coupling variables can be treated as a known matching disturbance. Each subsystem is discussed in terms of closed-loop stability. As additional contributions, we propose a thrust allocation algorithm which can cope with actuation faults and/or failures, so that the dynamic nonlinear controller does not require any modification of the control law. Moreover, the controller design variables are tuned with a state-of-the-art heuristic algorithm. Finally, the proposed overall Fault Tolerant Dynamic Surface Control scheme, namely FT-DSC, is compared with classical nonlinear control and thruster allocation approaches, in a highly realistic simulation scenario, including saturations, actuator dynamics, sensor noises, time discretization and faults. In practical terms, the proposed control law provides fail-operational trajectory tracking capabilities to a ROV in case of loss of efficiency of one or more thrusters, up to a thruster failure. Moreover, it can be easily applied to different types of ROVs, since the control design parameters are automatically tunable. The simulation results show that the proposed control architecture scheme is a viable solution to the research problem of trajectory tracking for a ROV in thruster faulty scenarios.

The paper is organized as follows. The mathematical model of the ROV is presented in Section 2. The DSC law is discussed and synthesized, and, in addition, the fault tolerant control allocation algorithm is shown in Section 3. The synthesis of PID, backstepping and sliding mode controllers are reported for comparison in Section 4, where the discussion of implementation details is also reported, as well as simulation results and comparisons in a complex scenario. Conclusions and final remarks end the work.

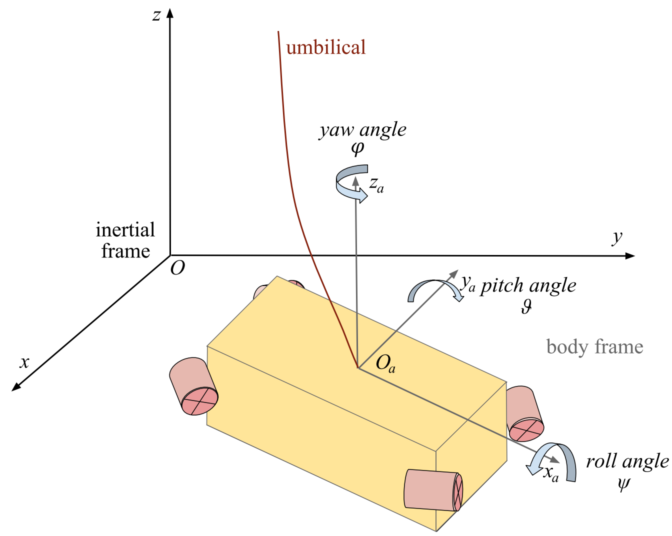

Fig. 1. ROV inertial and body frames.

2. ROV mathematical model

We consider the system as a rigid body, so the dynamical model has six degrees of freedom, corresponding to three spatial positions and three orientation angles [5,28]. We define a fixed inertial reference frame $R(O, x, y, z)$ and a body reference frame $R'(O_a, x_a, y_a, z_a)$, as reported in Fig. 1. The ROV position is defined by the vector $\vec{OO_a}$ that starts from the origin of the fixed reference and ends in the origin of the body reference frame; the ROV orientation is expressed by the conventional roll (ψ), pitch (θ), and yaw (φ) angles.

Let assume that:

- ROV depth is independently controlled by the surface vessel, while the ROV is able to move, thanks to its thrusters, along a horizontal plane at constant depth;
- pitch and roll angles can be neglected in any operational condition ([28]), because their amplitude is very low, so their influence on the dynamical model is irrelevant.

Following the procedure described in related works [5,28], the 3-DOF dynamical model in the earth fixed frame can be written as: