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A Nonlinear System with Coupled Switching Surfaces for Remotely Operated Vehicle Control

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Abstract: The paper is devoted to a new nonlinear discontinuous control algorithm and its applications in underwater robotics. The proposed approach is based on the usage of a relay control signals and coupled switching surfaces in order to improve the characteristics of a system. The choice of nonlinear switching functions to approximate own phase trajectories of a system in a case of relay control inputs, makes possible to get fast transient processes and high energy effectiveness. The derived approach is proven by applying it for controlling a remotely operated vehicle with parameters from a real ROV. Simulation results show the effectiveness of the proposed approach.

Keywords: discontinuous control, nonlinear switching surface, sliding mode, remotely operated vehicle

1. INTRODUCTION

In the last years, due to the rapid developments of the technology, the development of underwater vehicles has remarkably attracted noticeable interest as a cost-effective solution for performing complex tasks in the underwater environment, such as rescue, resource exploration, military, oil detection, etc., see for example [Yuh, 2000, Aguiar and Hespanha, 2007]. The control of such vehicles is particularly challenging due to their particular features which make the control system synthesis really difficult. Namely, the main difficulties are due to the nonlinearities of the underwater vehicle dynamics, to the parametric uncertainties, and to the underwater environment disturbances ([Goheen and Jefferys, 1990, Nie et al., 2000, Antonelli, 2014]).

During the past decades, many control schemes have been reported in the literature, such as nonlinear control, robust control, Variable-Structure Systems (VSSs), neural networks control and others ([Yoerger and Slotine, 1985, Goheen and Jefferys, 1990, Yuh, 1990, Goheen, 1991, Healey and Lienard, 1993, Unar and Murray-Smith, 1999, Antonelli et al., 2001, Wang and Lee, 2003, Corradini et al., 2009, Herman, 2009, Corradini et al., 2010, 2011, Antonelli, 2014, Kim et al., 2014, Ghommam and Saad, 2014]).

In this paper, a nonlinear algorithm for discontinuous control is proposed and applied to an underwater vehicle with parameters from a real one, namely a Remotely Operated Vehicle (ROV). The proposed algorithm finds a possible solution to one of the main disadvantages of the discontinuous control and the Sliding mode (SM), regarding the low level of energy effectiveness and unfavorable work conditions for actuators while sliding regime (chattering) occurs.

The main features of our proposed discontinuous control mechanism are following. First, coupled switching surfaces closely located in the system state space are used for a relay control. In a sector between these switching surfaces, the control signal is assigned equal to zero. If chattering occurs, oscillating control signal is unipolar switching between zero and its extreme value of appropriate sign in contrast with conventional VSS and relay systems. Control has the form of a commonly used pulse width modulated signal. Secondly, the switching functions are chosen to be nonlinear in order to approximate the system phase trajectories in case of relay control inputs, and such that to get fast transient processes and high energy effectiveness. The proposed solution represents an efficient and easy-to-use tool for controlling underwater vehicles, such as ROVs.

The paper is organized as follows. Section 2 briefly describes some features of discontinuous control systems

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and introduces an idea of usage of the coupled switching surfaces. The mathematical model of the ROV, which has been chosen for numerical simulations, is presented in Section 3. Results of computer simulations of the proposed relay system with coupled nonlinear switching surfaces for controlling a ROV, are given and discussed in Section 4. Final remarks conclude the paper.

2. DISCONTINUOUS CONTROL SYSTEM WITH COUPLED SWITCHING SURFACES

Discontinuous control in conventional systems of an appropriate class, such as VSS and relay systems, as a rule, can be written in the form

$$u = \begin{cases} u^+, \ s(x) > 0 \\ u^-, \ s(x) < 0 \end{cases} \quad (1)$$

with $s(x) = s(x_1, x_2, \ldots, x_n)$ is the pre-designed switching surface in the state space with coordinates $x_1, x_2, \ldots, x_n$, where $s(x) = 0$ (Fig. 1). Accordingly to [Utkin, 1981], the

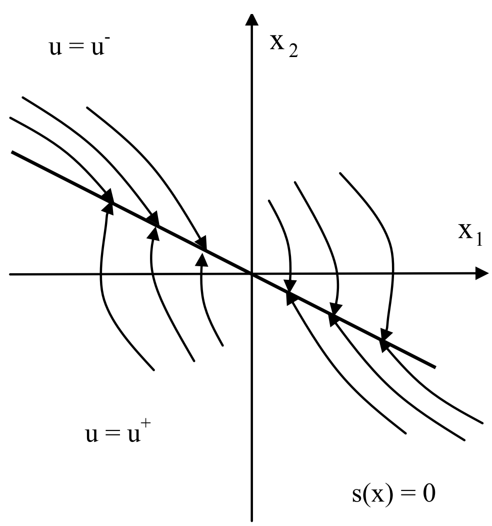

Fig. 1. Sliding mode in discontinuous control system.

condition of sliding mode existence is

$$s(x)\dot{s}(x) < 0 \quad (2)$$

This inequality means that system trajectories tend to the switching surface from both its sides. Discontinuous control law in Eq. (1) is realized by relay element of "sign" type. Starting from the time instant of switching surface reaching (namely, point t_0 on Fig. 2), relay signal has a form of bipolar meander of high frequency, as shown in Fig.2. The effective (equivalent) control is determined by the average signal component, which is, in common case, relatively small. Hence, as a consequence of chattering, extending energy expenditure takes place. Moreover, the fast changing polarity of the control signal is an unfavorable work condition for the actuators.

In order to overcome these disadvantages, a new control algorithm with nonlinear coupled switching surfaces is proposed in this paper. The essence of the developed approach consists of constructing a pair of closely located switching surfaces in the system state space. This pair can be considered as any splitting of original surface $s(x) = 0$

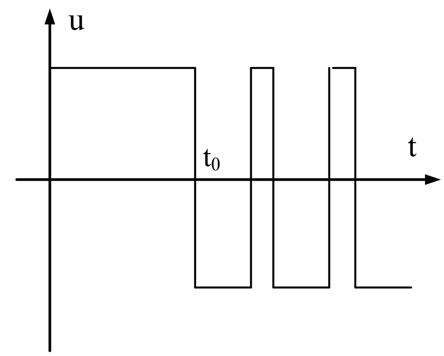

Fig. 2. Discontinuous control signal.

into two surfaces $s_1(x) = 0$ and $s_2(x) = 0$, which form thin sectors (Fig. 3). In these sectors, the control signal is assigned to zero. Outside of these sectors, the control is similarly as in the conventional VSS; thus

$$u = \begin{cases} u^+, \ s_1(x) > 0, s_2(x) > 0 \\ 0, \quad s_1(x)s_2(x) < 0 \\ u^-, \ s_1(x) < 0, s_2(x) < 0 \end{cases} \quad (3)$$

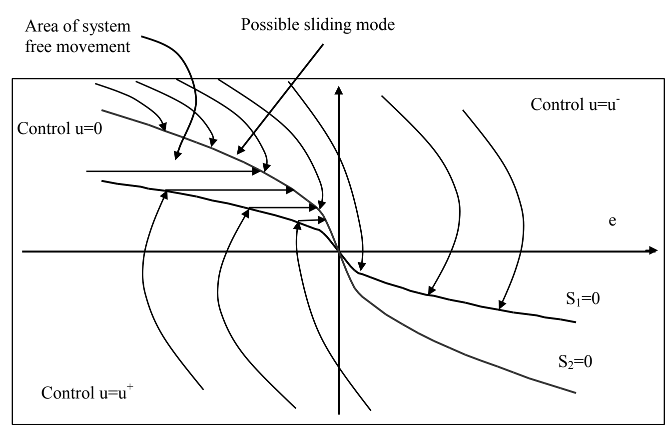

Fig. 3. Discontinuous control system with coupled switching surfaces.

This is an important advantage on the usage of this approach. In detail, from the phase portrait shown in Fig. 3, it is possible to see that there is an area where the system has a free motion, and this brings the representative point to the switching surfaces one, on which the sliding mode begins. The proposed switching surfaces design lets the control signal in sliding mode to be unipolar (see Fig. 4). As seen, in the considered case, the discontinuous controller is analogous to the pulse width modulator and it results to be effective from the energetic point of view in comparison with the conventional VSS [Markin and Dyda, 2000, Dyda, 2003].

Another significant feature of proposed approach regards the choice of the nonlinear switching functions to approximate own phase trajectories of a system in case of relay control inputs; this makes possible to get fast transient processes and high energy effectiveness. A motivation of the chosen function is provided in Section 4.