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A chattering-free sliding-mode controller for underwater vehicles with fault-tolerant infinity-norm thrust allocation

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ABSTRACT

There are two objectives to this paper. First, a chattering-free sliding-mode controller is proposed for the trajectory control of remotely operated vehicles (ROVs). Second, a new approach for thrust allocation is proposed that is based on minimizing the largest individual component of the thrust manifold. With regards to the former, a new adaptive term is developed that eliminates the high-frequency control action inherent in a conventional sliding-mode controller. As opposed to the common adaptive approach, the new adaptive term does not require the linearity condition on the dynamic parameters and the creation of a regressor matrix. In addition, it removes the need for a *priori* knowledge of upper bounds on uncertainties in the dynamic parameters of the ROV. With regards to the latter, it is demonstrated that minimizing the l_∞ norm (infinity-norm) of the thrust manifold ensures low individual thruster forces. The new control and thrust allocation concepts are implemented in numerical simulations of a work class ROV, and the chattering-free nature of the controller is demonstrated during typical ROV manoeuvres. In the simulation studies, the l_∞ norm-based thrust allocation problem is cast as a linear programming problem that allows direct incorporation of the thruster saturation limits and a fault-tolerant property. To achieve real-time solution rates for the l_∞ norm-based thrust allocation problem, a recurrent neural network is designed. In the simulation studies, the l_∞ norm-based thrust allocation provides smaller maximum absolute value of the largest component of the thrust manifold than that of a conventional l_2 norm (2-norm) minimization, satisfies the saturation limits of each thruster, and accommodates faults that are introduced arbitrarily during the manoeuvre.

1. Introduction

Remotely operated vehicles (ROVs) play an important role in a number of shallow and deep-water missions for marine science, oil and gas extraction, exploration, and salvage. In these applications, the motions of the ROV are guided either by a human pilot on a surface support vessel through an umbilical cord providing power and telemetry, or by an automatic pilot. In the case of automatic control, ROV state feedback is provided by acoustic and inertial sensors, and this state information along with a controller strategy is used to drive several conventional thrusters arranged on the ROV chassis.

In the existing literature, several different automatic control approaches have been applied to control ROV motion such as the H_∞ approach (Conte and Serrani, 1998), adaptive control techniques (Antonelli et al., 2001, 2003), sliding-mode control (Yoerger and Slotine, 1985; Slotine and Coetsee, 1986; Healey and Lienard, 1993; Antonelli, 2003), fuzzy-logic control (Debitetto, 1994; Kato, 1995), and neural network methods (Ishii and Ura, 2000; Kodogiannis, 2003; Pepijn et al., 2005; Van de Ven et al., 2005). It has been shown that the model-based sliding-mode approach is an effective means of controlling an ROV, largely due to its ability to tolerate imprecision in the dynamics model (Yoerger and Slotine, 1985; Slotine and Coetsee, 1986). However, one major drawback of the sliding-mode approach is the high frequency of control action (chattering). This high-frequency control activity causes high heat losses in electrical power circuits and premature wear in actuators. In addition, the high control activity may excite unmodelled high-frequency dynamics, which in turn causes controller performance degradation. To eliminate or reduce chattering, various methods such as the boundary layer method (Yoerger and Slotine, 1985; Slotine and Shastry, 1983) and the disturbance compensation method (Elmali and Olgac, 1992; Zeinali and Notash, 2007) have been presented. The boundary layer approach makes the control activity continuous within the boundary layer and discontinuous outside the boundary layer. In this work, a disturbance compensation method is utilized.

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To eliminate chattering, the disturbance compensation approach replaces the discontinuous term of a conventional sliding-mode controller with an estimate of the uncertainties in an adaptive manner. In the current work, a disturbance compensation approach discussed by Zeinali and Notash (2007) for land-base manipulators is extended to mobile-base ROV systems.

To ensure manoeuvrability, the ROV thruster arrangement is redundant: there are more thrusters than there are active vehicle degrees of freedom. Due to the excess thrusters, there are an infinite number of ways to allocate the pilot's commanded generalized force over the existing thrusters. As such, an optimal thrust allocation must be selected by applying criteria to distinguish the various options. In this work, a new definition for optimal thrust distribution is proposed.

A prominent approach to the thrust allocation problem is the 2-norm (l_2 norm)-based solution in which the sum of the squares of the individual thruster forces is minimized. In Antonelli (2003), a pseudo-inverse solution, and in Fossen (1994), Sordalen (1997), and Omerdic and Roberts (2004), a weighted pseudo-inverse are used to generate an optimal distribution of a commanded generalized force. The pseudo-inverse method has the advantage of being relatively simple to compute. Pseudo-inverse solutions correspond to the minimization of either the l_2 norm or a weighted l_2 norm of the thrust manifold. However, the l_2 norm-based solution does not necessarily minimize the magnitudes of the individual thrusts, and can generate thrust demands that may exceed an individual thruster's saturation point. In addition, there could be an unequal distribution in the thrust manifold leading to a relatively high thrust demand for a particular thruster. In such cases, there exists a potential for a loss of manoeuvrability on subsequent control steps. The disadvantages of the l_2 norm-based optimization were reported for land-base manipulators by Arati and Walker (1997).

Furthermore, the pseudo-inverse method (l_2 norm minimization) does not afford easy implementation of thruster saturation limits (Omerdic and Roberts, 2004). It was reported by Durham (1993) that, even if thruster saturation is implemented, the pseudo-inverse solution is not guaranteed to satisfy the saturation constraints. The pseudo-inverse solution was also used for the thruster allocation problem by Sarkar et al. (2002). To generate reference thruster values that do not exceed the saturation limit of each thruster, Sarkar et al. (2002) employed a dynamic state feedback method.

In the current work, it is proposed that the complications associated with the l_2 norm-based solutions be avoided by using the infinity-norm (l_∞ norm) as the criterion in the thrust allocation. (The l_∞ norm is defined as the absolute value of the largest component of the thrust manifold). By using the l_∞ norm to gauge optimality of a thrust distribution, the largest single thrust in the distribution is minimized. The current work shows how the l_∞ norm thruster allocation can be cast as a constrained linear programming problem that allows direct implementation of thruster saturation limits and a fault-tolerant property. As pointed out by Sarkar et al. (2002), the allocation of thruster force problem in the presence of thruster faults and saturation limits for ROV systems has not been studied extensively. To obtain real-time computation rates for the linear programming problem, a recurrent neural network is proposed. An l_∞ norm-based thruster allocation has been preliminarily discussed by the authors of the current work in Soylu et al. (2007).

The efficacy of the proposed fault-accommodating thrust allocation scheme with the chattering-free sliding-mode control is demonstrated through numerical simulation studies on the ROPOS vehicle operated by the Canadian Scientific Submersible.

2. Dynamics and control

2.1. Dynamics of an ROV

The dynamic equations of motion of ROVs in the body-fixed frame can be represented as (Fossen, 1994)

$$\mathbf{M}\dot{\boldsymbol{q}} + \mathbf{C}(\dot{\boldsymbol{q}})\boldsymbol{q} + \mathbf{D}(\dot{\boldsymbol{q}})\boldsymbol{q} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}$$
$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{q} \tag{1}$$

where $\boldsymbol{q} = [u \quad v \quad w \quad p \quad q \quad r]^{\mathrm{T}}$ is the ROV spatial velocity state vector with respect to its body-fixed frame, and $\boldsymbol{\eta} = [x \quad y \quad z \quad \phi \quad \theta \quad \psi]^{\mathrm{T}}$ is the position and orientation state vector with respect to the inertial frame. The coordinate systems considered are illustrated in Fig. 1.

In Eq. (1), the spatial transformation matrix between the inertial frame and the ROV's body-fixed frame can be defined through the Euler angle transformation (Fossen, 1994), denoted by $\mathbf{J}(\boldsymbol{\eta}) \in \mathbb{R}^{6\times 6}$. The term $\mathbf{M}(\boldsymbol{q}) \in \mathbb{R}^{6\times 6}$ is the inertia matrix including the added mass effects, $\mathbf{C}(\boldsymbol{q}) \in \mathbb{R}^{6\times 6}$ is the matrix of centrifugal and Coriolis terms, $\mathbf{D}(\boldsymbol{q}) \in \mathbb{R}^{6\times 6}$ is the drag matrix, $\mathbf{g}(\boldsymbol{\eta}) \in \mathbb{R}^{6}$ is the vector of gravity and buoyancy forces and moments, and finally $\boldsymbol{\tau} \in \mathbb{R}^{6}$ is the control forces and moments acting on the ROV centre of mass.

Eq. (1) can be represented in the inertial reference frame as (Fossen, 1994)

$$\boldsymbol{f} = \mathbf{M}_\eta(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}} + \mathbf{C}_\eta(\boldsymbol{q},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \mathbf{D}_\eta(\boldsymbol{q},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \mathbf{g}_\eta(\boldsymbol{\eta}) = \mathbf{J}^{-\mathrm{T}}\boldsymbol{\tau} \tag{2}$$

where $\mathbf{M}_\eta(\boldsymbol{\eta}) = \mathbf{J}^{-\mathrm{T}}\mathbf{M}\mathbf{J}^{-1}$, $\mathbf{C}_\eta(\boldsymbol{q},\boldsymbol{\eta}) = \mathbf{J}^{-\mathrm{T}}[\mathbf{C} - \mathbf{M}\mathbf{J}^{-1}\dot{\mathbf{J}}]\mathbf{J}^{-1}$, $\mathbf{D}_\eta(\boldsymbol{q},\boldsymbol{\eta}) = \mathbf{J}^{-\mathrm{T}}\mathbf{D}\mathbf{J}^{-1}$ and $\mathbf{g}(\boldsymbol{\eta}) = \mathbf{J}^{-\mathrm{T}}\boldsymbol{g}$. The dynamics of an ROV are assumed to have the following structural properties (Fossen, 1994):

Property 1. The inertia matrix $\mathbf{M}_\eta$ is symmetric and positive definite, i.e., $\mathbf{M}_\eta^{\mathrm{T}} = \mathbf{M}_\eta$;

Property 2. Matrix $\dot{\mathbf{M}}_\eta - 2\mathbf{C}_\eta$ is skew symmetric, i.e., for any vector ζ, $\zeta^{\mathrm{T}}(\dot{\mathbf{M}}_\eta - 2\mathbf{C}_\eta)\zeta = 0$.

Eq. (2) can be written in a more compact form of

$$\boldsymbol{f} = \mathbf{M}_\eta(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}} + \boldsymbol{h}_\eta(\boldsymbol{q},\boldsymbol{\eta}) \tag{3}$$

where $\boldsymbol{h}(\boldsymbol{q},\boldsymbol{\eta}) = \mathbf{C}_\eta(\boldsymbol{q},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \mathbf{D}_\eta(\boldsymbol{q},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \mathbf{g}_\eta(\boldsymbol{\eta})$. As mentioned earlier, the ROV dynamics are dominated by hydrodynamic loads, and it is difficult to accurately measure or estimate the hydrodynamic coefficients that are valid for all ROV operating conditions and instrument and tether configurations. As such, the system dynamics are not exactly known. Therefore, the system dynamics given in Eq. (3) can be written as the sum of estimated dynamics $\hat{\boldsymbol{f}}$ and the unknown dynamics $\tilde{\boldsymbol{f}}$:

$$\boldsymbol{f} = \hat{\boldsymbol{f}} + \tilde{\boldsymbol{f}} \tag{4}$$

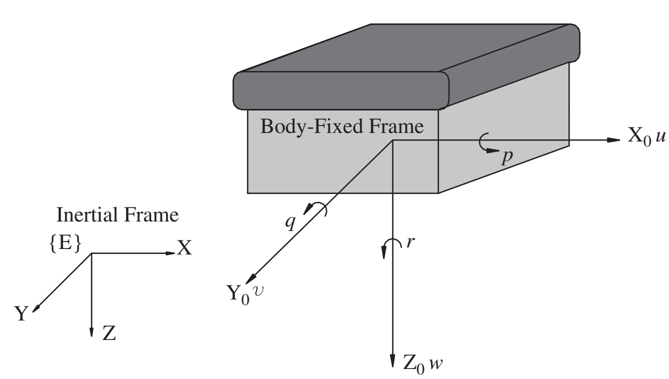

Fig. 1. Coordinate systems.